ANL/EES-TM-319

Radioactive Waste Isolation in Salt: Peer Review of the Office of Nuclear Waste Isolation's Draft Report on a Multifactor Test Design to Investigate Uniform Corrosion of Low-Carbon Steel

R. A. Paddock, A. Lerman, J. D. Ditmars, D. D. Macdonald,
J. P. Peerenboom, G. S. Was, and W. Harrison

ARGONNE NATIONAL LABORATORY
Energy and Environmental Systems Division

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THE UNIVERSITY OF CHICAGO for U. S. DEPARTMENT OF ENERGY
under Contract W-31-109-Eng-38

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Printed in the United States of America. Available from National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue, Argonne, Illinois 60439

ANL/EES-TM-319

RADIOACTIVE WASTE ISOLATION IN SALT:

PEER REVIEW OF THE OFFICE OF NUCLEAR WASTE ISOLATION'S DRAFT REPORT ON A MULTIFACTOR TEST DESIGN TO INVESTIGATE UNIFORM CORROSION OF LOW-CARBON STEEL

by

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Completed January 1986
(except for App. C)

Published January 1987

work sponsored by

U.S. DEPARTMENT OF ENERGY
Office of Civilian Radioactive Waste Management
Salt Repository Project Office

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NOTICE TO READERS

At the request of the Salt Repository Project Office (SRPO), Argonne National Laboratory conducted a review of the Office of Nuclear Waste Isolation's report entitled "Multifactor Test Design to Investigate Uniform Corrosion of Low-Carbon Steel in a Nuclear Waste Salt Repository Environment," O/TM-71.* This report advances an experimental design for testing the uniform corrosion of low-carbon steel and recommends a full factorial matrix of 250 tests with four experimental factors: time, temperature, oxygen fugacity, and magnesium concentration. A multi-disciplinary panel of engineers and scientists was used to develop the test matrix.

Specific instructions were provided to the review panel (see Appendix A). The panel also reviewed the document from a broad point of view. Valuable comments were provided by the panel. Actions to be taken in response to the review comments and recommendations are included in Appendix C of this report.

R.C. Wunderlich
Deputy Project Manager
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*A microfiche copy of this report is attached to the inside back cover of this report.

FOREWORD

Documents are being submitted to the Salt Repository Project Office (SRPO) of the U.S. Department of Energy (DOE) by Battelle Memorial Institute's Office of Nuclear Waste Isolation (ONWI) to satisfy milestones of the Salt Repository Project of the Civilian Radioactive Waste Management Program. Some of these documents are being reviewed by multidisciplinary groups of peers to ensure DOE of their adequacy and credibility. Adequacy of documents refers to their ability to meet the requirements of the U.S. Nuclear Regulatory Commission and the U.S. Environmental Protection Agency, as enunciated in 10 CFR Part 60 and 40 CFR 191, respectively, as well as those of the Nuclear Waste Policy Act of 1982. Credibility of documents refers to the validity of the assumptions, methods, and conclusions, as well as to the completeness of coverage.

Since late 1982, Argonne National Laboratory has been under contract to DOE to conduct multidisciplinary peer reviews of program plans and reports covering research and development activities related to siting and constructing a mined repository in salt for high-level radioactive waste. This report summarizes Argonne's review of an August 1985 draft internal technical memorandum by ONWI entitled *Multifactor Test Design to Investigate Uniform Corrosion of Low-Carbon Steel in a Nuclear Waste Salt Repository Environment.*

Argonne was requested by DOE to review this memorandum on October 21, 1985 (see App. A). This review report and the letter from Argonne to DOE, also included in App. A, constitute Argonne's response to that request. The review procedure involved obtaining written comments on the memorandum from three members of Argonne's core peer review staff, one other Argonne expert, and three off-site peer review panelists who are experts in relevant research areas. Chicago-area peer review panelists met at Argonne on November 20, 1985, and reviewer comments were integrated into this report by the review session chairman, with the assistance of Argonne's core peer review staff. Panelists did not contact ONWI personnel, and none of the panelists have been involved in any programs sponsored by DOE or directed by ONWI such that their participation in the review could be construed as a conflict of interest. All peer review panelists were asked whether they concur in the way in which their comments, where incorporated, are represented in this report (see App. B). The initial draft of this report was sent to SRPO on December 13, 1985. Action statements based on ONWI's response to the January 1986 final draft of this review report are detailed in App. C.

PREVIOUSLY PUBLISHED REPORTS IN THE SERIES

"RADIOACTIVE WASTE ISOLATION IN SALT"

ANL/EES-TM-242	Peer Review of the Office of Nuclear Waste Isolation's Geochemical Program Plan (Feb. 1984)
ANL/EES-TM-243	Peer Review of the Office of Nuclear Waste Isolation's Socioeconomic Program Plan (Feb. 1984) (revised July 1984)
ANL/EES-TM-246	Peer Review of the Office of Nuclear Waste Isolation's Plans for Repository Performance Assessment (May 1984)
ANL/EES-TM-254	Peer Review of the Office of Nuclear Waste Isolation's Reports on Preferred Repository Sites within the Palo Duro Basin, Texas (June 1984)
ANL/EES-TM-256	Special Advisory Report on the Status of the Office of Nuclear Waste Isolation's Plans for Repository Performance Assessment (Oct. 1983)
ANL/EES-TM-258	Peer Review of the Office of Nuclear Waste Isolation's Plan to Decommission and Reclaim Exploratory Shafts and Related Facilities (July 1984)
ANL/EES-TM-259	Peer Review of the Office of Nuclear Waste Isolation's Final Report on the Organic Geochemistry of Deep Groundwaters from the Palo Duro Basin, Texas (Aug. 1984)
ANL/EES-TM-260	Peer Review of the Texas Bureau of Economic Geology's Report on the Petrographic, Stratigraphic, and Structural Evidence for Dissolution of Upper Permian Bedded Salt, Texas Panhandle (Aug. 1984)
ANL/EES-TM-261	Peer Review of the Office of Nuclear Waste Isolation's Report on Functional Design Criteria for a Repository for High-Level Radioactive Waste (Aug. 1984)
ANL/EES-TM-262	Peer Review of the D'Appolonia Report on Schematic Designs for Penetration Seals for a Repository in the Permian Basin, Texas (Sept. 1984)
ANL/EES-TM-263	Peer Review of the Office of Nuclear Waste Isolation's Reports on Multifactor Life Testing of Waste Package Materials (Sept. 1984)
ANL/ES-147	Rationale and Methodology for Argonne-Conducted Reviews of Site Characterization Programs (July 1985)

PREVIOUSLY PUBLISHED REPORTS IN THE SERIES

"RADIOACTIVE WASTE ISOLATION IN SALT" (Cont'd)

ANL/EES-TM-290	Geochemistry of Brine in Rock Salt in Temperature Gradients and Gamma-Radiation Fields -- A Selective Annotated Bibliography (July 1985)
ANL/EES-TM-292	Peer Review of Westinghouse Electric Corporation's Report on Reference Conceptual Designs for a Repository Waste Package (Oct. 1985)
ANL/EES-TM-316	Peer Review of the Office of Nuclear Waste Isolation's Draft Report on an Issues Hierarchy and Data Needs for Site Characterization (Dec. 1986)

CONTENTS

PEER REVIEW PANEL MEMBERS x

ACKNOWLEDGMENTS xi

SUMMARY OF RECOMMENDATIONS 1

1 INTRODUCTION 5

2 MAJOR AREAS OF CONCERN 6

2.1 Relationship of Planned Testing to the Waste Package Program 6
2.2 Degree of Adherence to the ONWI-501 Methodology 8
2.3 Consensus Procedures 8
2.4 Treatment of Uncertainty 9
2.5 Selection of Controlling Factors 10
2.6 Description of Test Procedures 13
2.7 Implementation Plan 15
2.8 Use of Available Information, Data, and Outside Expertise 16
2.9 Other Concerns 16

3 PAGE-BY-PAGE COMMENTARY 18

REFERENCES 35

APPENDIX A: Correspondence Related to the Peer Review 37

APPENDIX B: Concurrence Sheet 43

APPENDIX C: Action to Be Taken on the Argonne Peer Review Panel Recommendations and Page-by-Page Comments 47

APPENDIX D: Credentials of Peer Review Panel Members 75

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A microfiche copy of the following unpublished document is attached to the inside back cover of this report: *Multifactor Test Design to Investigate Uniform Corrosion of Low-Carbon Steel in a Nuclear Waste Salt Repository Environment*, Office of Nuclear Waste Isolation internal technical memorandum, O/TM-71, Battelle Memorial Institute, Columbus, Ohio (Aug. 1985).

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The credentials of the panel members are summarized in App. D.

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ACKNOWLEDGMENTS

Mary F. Warren is thanked for her thorough technical editing of this report. Amy L. Anderson provided general assistance to Argonne's core peer review staff during the review session and during the drafting of this report.

RADIOACTIVE WASTE ISOLATION IN SALT:

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SUMMARY OF RECOMMENDATIONS

This report documents Argonne National Laboratory's review of an internal technical memorandum prepared by Battelle Memorial Institute's Office of Nuclear Waste Isolation (ONWI) entitled *Multifactor Test Design to Investigate Uniform Corrosion of Low-Carbon Steel in a Nuclear Waste Salt Repository Environment.* The several major areas of concern identified by peer review panelists are important to the credibility of the test design proposed in the memorandum and are not adequately addressed there. These areas of concern, along with specific recommendations to improve their treatment, are discussed in detail in Sec. 2 of this report. The following recommendations, which were abstracted from those discussions, are presented essentially in the order in which they are introduced in Sec. 2.

1. The relationship of the proposed tests to the overall waste package program of the Salt Repository Project should be clearly and simply stated.

2. A basic conceptual model that could be used to estimate container life expectancy under repository conditions from the test results should be supplied.

3. The assumption that a steady state corrosion rate that will persist for several hundred years will be reached within the five-year test period should be better supported.

4. The fact that the methodology described in the ONWI-501 report* was eventually abandoned by the panel in developing the test matrix and the implementation plan should be mentioned earlier and more explicitly in the memorandum.

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*R.E. Thomas and R.W. Cote, *Methodology for Predicting the Life of Waste-Package Materials and Components Using Multifactor Accelerated Life Tests*, ONWI-501, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, Ohio (Sept. 1983).

5. The text should state that the proposed test design does not include accelerated life testing as described in ONWI-501, and the reasons the panel chose not to consider such testing should be given.

6. The techniques used by the panel in arriving at consensus positions should be described.

7. The technical arguments and the data used to eliminate the "weaker and less-substantiated" individual predictions of corrosion rates from Table 3-1 should be fully described.

8. Uncertainties in judgment and measurement should be incorporated into the predictions of corrosion rates and the test design process.

9. Consideration should be given to testing over a broader range of values for the controlling factors of temperature, oxygen concentration, and magnesium concentration to allow for any adjustments in anticipated repository conditions that may occur as the Salt Repository Project evolves or to investigate limiting cases, such as corrosion in a brine free of magnesium.

10. The supplementary tests to study the effects of metal microstructure on corrosion rate should be redesigned to do more than just confirm that a metallurgical effect exists.

11. More detailed justification should be given for eliminating gamma radiation, pressure, detailed brine composition, brine flow (refreshment rate), and the presence of welds as possible controlling factors for the tests.

12. The manner in which the proposed tests are to be conducted should be described. The description need not give detailed test procedures but should clarify those aspects of the test procedures that could affect the test results and their interpretation.

13. The decision processes and criteria used to arrive at the proposed implementation plan for the main tests should be discussed.

14. Because of the profound effect the supplementary tests could have on the design and implementation of the main tests, the apparently secondary role these supplementary tests play in the total test design should be explained and justified, and an implementation plan for these tests should be presented.

15. Consideration should be given to the flexibility of the overall test design and the criteria to be used to identify the need for changes in the test design.

16. The extent to which the panel made use of available information, data, and outside expertise in selecting the controlling factors for the tests and predicting expected corrosion rates should be more completely and carefully documented.

17. More consideration should be given to the form in which the estimated corrosion rates are presented, to the types of conclusions that can be drawn from the rates, and to the relationship of these conclusions to basic physical and chemical principles.

18. If the panel considers an understanding of the mechanism of amakinite formation during corrosion to be important, the text should emphasize the need for additional research.

19. The purpose and utility of the technique described in App. D, both of which seem to be incorrectly stated, should be more carefully considered and more fully described.

20. If the panel actually intends that the technique described in App. D be used to "prune" the test matrix, this application of the technique should be more clearly described.

1 INTRODUCTION

Isolation of high-level radioactive wastes in a geologic repository in salt requires a waste package, which consists of the waste form, waste canister, disposal container, and any other components engineered to contain the waste. The disposal container must contribute substantially to the ability of the overall waste package system to contain radionuclides for long periods (300-1000 years). The Salt Repository Project Office (SRPO) of the U.S. Department of Energy (DOE) is considering low-carbon steel as a construction material for the disposal container. To evaluate the suitability and performance of this material, SRPO directed Battelle Memorial Institute's Office of Nuclear Waste Isolation (ONWI) to develop a test program to investigate uniform corrosion of low-carbon steel under salt repository conditions using the approach described in Thomas and Cote (1983, ONWI-501).

The approach described in ONWI-501 assigns responsibility for the test design to a panel of experts. The proposed test design and the supporting documentation produced by the expert panel are contained in an unpublished internal technical memorandum (Gopal et al., 1985, O/TM-71) entitled *Multifactor Test Design to Investigate Uniform Corrosion of Low-Carbon Steel in a Nuclear Waste Salt Repository Environment.* This internal technical memorandum is the subject of this peer review conducted by Argonne National Laboratory.

No specific guidance was provided to Argonne by DOE/SRPO on how the review was to be conducted; however, a list of areas of concentration for the review was prepared by DOE/SRPO to assist in the review process (see App. A). During the peer review session at Argonne, the written review comments were discussed, and several major areas of concern with respect to O/TM-71 were identified. The review session chairman then drafted the present report based on the discussions and the written comments. The relationship between the present report and the areas of concentration provided to Argonne by DOE/SRPO is described in a letter from Argonne to DOE/SRPO (also included in App. A).

This review report consists of two main parts: Sec. 2 discusses the major areas of concern with respect to O/TM-71 that were identified by the panelists during the review session meeting, and Sec. 3 constitutes a page-by-page compilation of specific comments and recommendations.

2 MAJOR AREAS OF CONCERN

During the peer review session meeting, the following major areas of concern were identified as important to the credibility of the proposed test design, but inadequately addressed in O/TM-71.

1. The relationship of the planned tests to the waste package program of the Salt Repository Project (e.g., waste package design and assessment of waste package performance).

2. The degree of adherence to the general methodology of ONWI-501 (Thomas and Cote, 1983) by the expert panel during the decision-making process.

3. The consensus procedures used throughout the panel's deliberations.

4. The treatment of uncertainty in establishing the consensus corrosion rates and in developing the test design.

5. The justification for selecting and rejecting potential controlling factors for the experiments.

6. The description of general test procedures.

7. The test implementation plan and the relationship between the supplementary tests and the main test matrix.

8. The use of available information, data, and outside expertise by the panel in developing the test design.

These areas of concern are discussed sequentially in Secs. 2.1-2.8. Several more specific concerns are discussed briefly in Sec. 2.9.

2.1 RELATIONSHIP OF PLANNED TESTING TO THE WASTE PACKAGE PROGRAM

The relationship of the planned tests to the overall waste package program of the Salt Repository Project should be clearly and simply stated. Although Sec. 5.0 indicates the relationship of the proposed test matrix to completed and ongoing tests in terms of specific test factors, the relationship between the planned tests and the programmatic objectives of completed and ongoing tests is never stated. On page 48, the text implies that the test matrix will drive the Waste Package Program Plan and related technical program plans. The reverse should be true; that is, the Waste Package Program Plan should spell out the objectives that must be achieved through the design of an appropriate test matrix.

The immediate objective of the corrosion test program presented in O/TM-71 is to provide uniform corrosion data and insight into the processes involved in uniform corrosion. These data and insights will be used to develop a corrosion model that can predict the behavior of and ultimately the life expectancy of low-carbon steel disposal containers in a geologic repository in salt. However, O/TM-71 does not explicitly explain the anticipated means of determining container failure as a result of uniform corrosion for either design or performance assessment purposes.

Implicit in O/TM-71 is the idea that the amount of container penetration can be calculated by integration over time once uniform corrosion rates are determined. However, the report does not indicate how this integration could be carried out for a container in a repository where environmental conditions will not be as simple as the test conditions and will most likely be changing. Sketches of possible variations in environmental conditions and expected corrosion rates and a conceptual model for predicting container life expectancy might help quantify what should be expected of the test program. For example, if conditions that lead to high corrosion rates are expected to exist in the repository for relatively short periods, it may not be necessary to predict these high corrosion rates very accurately. However, if these high corrosion rates are expected to persist for long periods, they may need to be predicted much more accurately. On the other hand, if repository conditions are such that corrosion rates are expected to be very low for a very long period, a relatively large degree of uncertainty in this very low corrosion rate may be acceptable because it could be compensated for by a small increase in container thickness.

Without at least a basic conceptual model that relates the expected results of the corrosion tests to container lifetimes, one cannot be sure that the test design will meet the waste package design and performance assessment needs of the Salt Repository Project. Factors or conditions that may eventually be important in predicting container lifetimes may not be addressed by the tests if the proposed test design is developed outside the framework of a conceptual model. For example, the corrosion rate at any given time may depend on the previous history of the material; changing conditions may disturb a protective magnetite corrosion layer; or unlimited brine may not be a conservative condition if changes in brine composition in limited-brine cases result in increased corrosion rates.

A concern related to using the results from the proposed tests to address waste package design and performance assessment requirements is the need to use the results of tests of five years' duration or less to predict container behavior over a 300- to 1000-year period. Although the panel indicates that the corrosion rate will probably reach a steady state within the five-year test period, this assumption is not well supported. In addition, no evidence or justification is provided to indicate that the corrosion rate obtained after five years will remain constant or will decrease for several hundreds of years. In any case, the concept of steady state may not have much meaning in a repository where conditions will be changing. Unless a fundamental understanding of corrosion mechanisms is gained from the proposed test design, the test results may be of limited value for waste package design and performance assessment.

The proposed test design does take into consideration the range of conditions expected in the repository. However, little consideration is given to the ultimate use of the test results except for the immediate goal of developing a corrosion model. In summary, to ensure that the test results will satisfy the waste package design and performance assessment needs of the Salt Repository Project, O/TM-71 should state how the test results will be used to predict container lifetimes under expected repository conditions.

2.2 DEGREE OF ADHERENCE TO THE ONWI-501 METHODOLOGY

The reviewed report seeks to record the activities of a multidisciplinary panel of engineers and scientists as it formulated a test design to study uniform corrosion of low-carbon steel. In some ways O/TM-71 documents the application of the methodology described in ONWI-501. However, it appears that the panel felt constrained to use the ONWI-501 methodology even though it did not find the methodology helpful in developing the test design. Explicit references to the panel's lack of confidence in both the predicted corrosion rates and the hierarchical trees developed as required by the methodology occur throughout O/TM-71. Although the ONWI-501 methodology may have served panel members well in terms of coming to grips with the inadequacy of the information available upon which to base the tests, many of the major decisions were reached outside the methodological framework. The report should state that fact, indicating that the actual test design was developed on a more ad hoc basis. In addition, the fact that the ONWI-501 methodology was eventually abandoned should be mentioned early in the report so that readers do not get the impression that the panel is attempting to add to the credibility of the proposed test design by having superficially adhered to the methodology.

The methodology presented in ONWI-501 is supposedly to be used to design accelerated life tests for predicting the life of waste package materials and components. Accelerated life tests are defined as tests that subject the test material to higher than expected stresses for shorter that expected periods. The test results are then used to estimate by extrapolation the behavior of the material under expected repository conditions over long periods. Although accelerated test design is mentioned in Sec. 1.1, the panel apparently did not consider accelerated testing as a means of solving the uniform corrosion problem. The report should state that the proposed test design does not include accelerated testing and explain why the panel chose not to consider such testing.

2.3 CONSENSUS PROCEDURES

The term "consensus" is used rather loosely in a number of different contexts throughout O/TM-71, and the techniques used to obtain consensus are not always stated. For example, the text makes clear that consensus corrosion rates were developed by taking geometric means of the predictions of individual panelists, but the techniques used to obtain consensus positions on key issues raised by the panel are not discussed. It is particularly relevant to know whether formal (e.g., Delphi method, nominal group approach, or decision analysis) or informal (e.g., simple voting) techniques were used in arriving at group consensus positions, and whether one or two of the panelists dominated at the meetings and perhaps overly influenced the other panel members. Safeguards taken to avoid these problems should also be described.

Section 2.1.4 states that the consensus test design will result from a team effort to identify the best inputs and eliminate the weaker and less-substantiated inputs to the design process. Obtaining consensus by eliminating the weaker and less-substantiated inputs seems somewhat inappropriate given (1) the concerns of the panelists about the lack of available data upon which to base predictions and (2) the failure of the panelists to represent their judgments probabilistically. In view of the level of uncertainty, the question of how certain inputs were determined to be weak and less substantiated should be addressed.

The factorial table of consensus corrosion rates is described in Sec. 3.6 and presented in Table 3-2. Apparently, individual panelists did not use the same data in making their predictions (Table 3-1). The report should explain more fully why all of the panelists except Westerman and Lee relied only on Pacific Northwest Laboratories data for predicting corrosion rates. A key question is whether the data sources were discussed before the panelists were asked to make their individual predictions. It is extremely important to clarify this point in light of the fact that Ballinger, Cunnane, and Kuhn all withdrew their predicted corrosion rates, which correspond to high-oxygen, low-magnesium conditions, and deferred to those of Lee and Westerman, which reflect a dominance of temperature over magnesium concentration and oxygen fugacity. As Tables 3-1 and 3-2 show, the resulting consensus corrosion rates for these sets of conditions were greatly affected by the withdrawal of the estimates of three of the panelists. The technical arguments advanced by Lee and Westerman, and any new data that may have been used, should be fully described.

Even after some of the individual estimates of corrosion rates were withdrawn, large differences were still evident among the remaining estimates. Better agreement might have been achieved by more thorough discussion of the nature of the individual estimates and by attempts to arrive at a greater degree of reliability in the estimates through more careful analysis of the fundamental data and mechanisms. The panel actually declares its lack of confidence in the consensus corrosion rates in several places. In fact, little use was made of these corrosion rates and the resulting hierarchical trees in developing the consensus test matrix (Table 3-3). In any case, the reasons why individual panelists accepted consensus corrosion rates so different from their individual estimates should be discussed. Readers cannot reasonably judge the value of the consensus corrosion rates in Table 3-2, as the rates are not necessarily representative of the individual predictions in Table 3-1.

2.4 TREATMENT OF UNCERTAINTY

A major deficiency in the methodology described in ONWI-501 is that neither measurement nor judgmental uncertainty is explicitly incorporated into the analysis. The panel acknowledges this deficiency in Sec. 3.12. While this issue may be considered to be a primarily methodological one, it has extremely important implications with respect to the meaningfulness of the information provided by the panelists.

With respect to measurement uncertainty, O/TM-71 states that the precision of corrosion rate determinations between replicate specimens is typically within 20%. This measurement uncertainty should be treated within the methodological framework to determine the number of replicates needed and to establish estimates of the accuracy and precision of the expected test results.

With respect to judgmental uncertainty, each panel member was asked to provide a predicted corrosion rate (i.e., a single number) for each of 16 combinations of dominant factors. Mathematically, providing a single value implies exact knowledge about the value provided. In fact, all panel members expressed concern about their lack of confidence (i.e., uncertainty) in their predictions because of insufficient information about the general corrosion process, including credible models for a repository environment. It would have been desirable to include uncertainty in a systematic and logical fashion, ideally by representing the expert judgments probabilistically. The incorporation of uncertainty would have eliminated the need for many of the simplifying and tenuous assumptions used in the analysis of the hierarchical trees. Even constructing probability distributions from the "point estimates" provided by the experts and including the measurement uncertainty in the corrosion-rate determinations would have been more satisfactory than viewing the problem deterministically.

As an example, the consensus corrosion rates in Table 3-2 for certain sets of conditions were greatly affected by the withdrawal of the estimates of three of the panelists. Eliminating some of the inputs might not have been necessary had uncertainty been included in the analysis.

It is not clear why the ONWI-501 methodology was applied, especially in view of the panel's conclusion that the estimated corrosion rates are not reliable because of the "lack of sufficient and relevant data and theoretical insight" (page 47). Given the lack of confidence in the predictions (as a result of uncertainty) and the tree structure, together with the failure of the methodology to treat uncertainty, the panel may not have needed to go through the motions. To help clarify this point, the panelists should state at what point it became apparent that the data were insufficient for eliminating tests from the test matrix. If the experts felt that way at the start of the process, applying the methodology may have been inappropriate.

2.5 SELECTION OF CONTROLLING FACTORS

The panel selected four fundamental variables, that is, factors to be controlled and monitored during the tests: time, temperature, oxygen fugacity, and magnesium concentration. Bounds for the values of these controlling factors in the experiments were established, and intermediate values were eventually selected for several of the factors. The discussion of these controlling factors (Sec. 3.0) seems rather narrowly focused. The assumptions necessary to go from the complex actual repository environment to the simplified conditions and factors needed to design tests should be discussed more thoroughly. The supplementary tests discussed in Sec. 4.0 provide a means of dealing with some of the issues associated with determining controlling factors. The reduction from the complex situation in a repository environment to a few controlling factors necessary for testing purposes should be discussed before the controlling factors selected for the tests are discussed.

The choice of specific values for the controlling factors to be used during the tests is not always adequately justified. The upper limit on the range of temperatures to be tested is set at 250°C, which is very close to the anticipated high temperature in the repository and does not allow for any adjustments in anticipated conditions that may occur as the Salt Repository Project evolves. An intermediate temperature of 100°C was justified as being representative of expected temperatures of a disposal container holding spent fuel from a pressurized water reactor over a 700-year period. This representative temperature (100 ± 30°C) is actually a range of temperatures from 70°C to 130°C, which almost spans the range between two of the other selected test temperatures (60°C and 150°C). Therefore, the justification for choosing the specific value of 100°C is not sound.

The upper limit for oxygen concentration is selected as representative of conditions soon after repository closure. The test conditions do not provide for unexpected adverse effects such as gas supersaturation in incoming brines. Therefore, the applicability of the test results to unexpected conditions may be limited.

The justification for selecting magnesium as a controlling factor representative of brine composition is not very satisfying, as discussed later in this section. However, if magnesium is important, and if low magnesium concentrations of 100 ppm are expected to affect corrosion rates, consideration should be given to including a magnesium concentration of zero, thereby obtaining a reference or control point for a brine free of magnesium. One set of supplementary tests examines the effects of a magnesium concentration of 2×10^5 ppm, which is only a factor of two higher than the upper limit used in the main test matrix. It is not apparent that increasing the magnesium concentration by a factor of two, when the basic range covers three orders of magnitude, is likely to provide important additional information on the effects of magnesium. If the effect of the magnesium concentration is expected to be that nonlinear, then the concentration intervals chosen for the main test matrix should be adjusted to accommodate this fact.

Another set of supplementary tests is designed to study the effect of metal microstructure on corrosion rate. However, as designed, these tests will do little except confirm that there is a metallurgical effect. Obtaining and testing five different heats of material from different steel foundries (as suggested on page 43) without controlling either the chemistry or microstructure (e.g., carbon content, impurity concentration, and grain size) will not help to identify any link between metallurgical variables and the corrosion rate. Because the tests are time consuming and expensive, they should be redesigned to do more than just confirm the existence of a metallurgical effect on corrosion rate.

Several controlling factors other than the four selected for the main test matrix and those considered by the supplementary tests were dismissed with only minimal technical justification. Those of particular concern include radiation, pressure, detailed brine composition, brine flow (refreshment rate), and the presence of welds. It may be possible to justify eliminating these additional controlling factors; however, they are of such potential importance in determining corrosion rates in a repository environment that they warrant more detailed consideration in Sec. 3.2.

On page 17 the text states that gamma radiation has been observed to have a strong effect on the corrosion rate of low-carbon steel only at dose rates exceeding 3000 rads per hour, but no data are given or sources referenced to support this claim. Radiation effects cannot be dismissed simply by assuming that they can be controlled by prudent waste package design. Long-term radiation effects may have a chronic effect on corrosion rates. In particular, the crystal structure and chemical composition of nearby rock salt and the chemical speciation of the brine may be affected. The exclusion of radiation effects does not seem to be warranted, at least on the basis of the information contained in O/TM-71.

Pressure is eliminated from consideration as a controlling factor because of its being limited to lithostatic values (about 2000 psi). While it is generally accepted that the fugacity of gases is not appreciably affected by pressures and temperatures in the ranges expected in the repository, it is important to consider and document the effect that high salt concentrations may have on the fugacity of reactive gases such as oxygen and hydrogen at these pressures and temperatures. The possible effect on corrosion rates of mechanical stress caused by pressure should also be addressed. Another consideration related to pressure is the potentially large quantity of hydrogen gas that might be generated by corrosion of containers of low-carbon steel. The fate of this hydrogen and its effect on the kinetics of the corrosion reaction should be addressed.

In the main tests proposed by the panel, the chemical composition of the brine is characterized by magnesium concentration alone. Little justification is given for selecting magnesium as the factor that characterizes brine composition, and no indication is given of the other cations and anions present in the test brines. Many different dissolved species in the brines of a repository could influence the overall corrosion rate. Before magnesium can be singled out as the appropriate factor to characterize brine composition for the purposes of designing corrosion tests, several questions pertaining to the role of dissolved species must be carefully considered. Can the role of an individual chemical species like magnesium be separated from the roles of other chemical characteristics of the brine, such as the total concentration of dissolved salts or the concentration of the major components? Does the nature of the anions in the brine, such as Cl^- alone versus Cl^- in combination with SO_4^{2-} or Br^-, play any role in determining the corrosion rate? And, finally, would changes in the total concentrations of dissolved species in the brine or changes in the chemical speciation (e.g., complexation, changes in pH and pOH, and occurrences of other oxidizing species like Cl_2) significantly affect the corrosion rates?

Brine flow (refreshment rate) is eliminated as a controlling factor because it relates to the design of the experimental system. However, the rate at which brine is brought to or carried away from the corroding surface may affect the corrosion rate because the brine composition may be continually changing as a result of such things as metal dissolution, liberation of corrosion products, or radiation effects. For example, Fe^{2+}, a corrosion product, may be oxidized to Fe^{3+} by oxygen or by oxidizing species formed by the interaction of radiation with the brine. The presence of a reducible species such as Fe^{3+} in the high-temperature concentrated brine may result in increased corrosion. Extensive work has been published on this subject by researchers investigating corrosion in nuclear power systems (e.g., Potter and Mann, 1965; Bignold et al., 1972; and Park, 1983). Corrosion rates of many centimeters per year have been observed. Furthermore, the corrosion reaction is often autocatalytic so that the system does not spontaneously passivate. The possibility of this type of corrosion process taking place under repository conditions should be considered in developing the test design. The effect of processes that depend on changes in brine composition may be either masked or accentuated by the brine flow (refreshment rate) used during a given laboratory test. Therefore, more consideration should be given to such factors before eliminating them as a controlling factor in the test design.

The panel acknowledges that welding during construction of disposal containers will introduce significant perturbations in the microstructure of the material. The text suggests that such perturbations may affect uniform corrosion rates in weld regions and that these effects must be investigated. However, the proposed test design does not include any details related to the testing of welds beyond the statement on page 18 that samples of welds should be included. From the point of view of predicting the integrity of the disposal container over a period of more than 300 to 1000 years, more consideration should be given in the design of the test program to the study of corrosion at welds.

2.6 DESCRIPTION OF TEST PROCEDURES

Although O/TM-71 states on page 37 that the procedures for conducting the proposed tests are discussed in Sec. 3.9, the discussion there is too limited to evaluate some of the issues associated with test design. While detailed test procedures are beyond the scope of O/TM-71, questions concerning the general test design do impinge on matters of experimental procedure. The document should describe how the proposed tests are to be conducted in sufficient detail to address the concerns discussed below.

The general type and size of the test vessels should be specified to give readers and those who will eventually develop detailed test plans a feel for the scale of the tests and how brine flow (refreshment rate), magnesium concentration, and oxygen concentration are to be controlled. Reasons should be given for suggesting welded static reaction vessels over seamless vessels for the hydrogen-pressure supplementary tests discussed on page 42.

The approximate size and shape of the samples to be tested should be discussed, as the precision with which corrosion rates can be determined depends somewhat on sample size. In addition, if the sample size is sufficiently large, it may be possible to detect and characterize some forms of localized corrosion such as pitting.

The number of replicate samples for tests in the main test matrix is five; the number of replicate samples for the supplementary tests is not specified. Justification should be given for choosing the number of replicates for each test condition. The results from replicate samples will presumably be used to estimate the precision of the experimentally determined corrosion rates. These corrosion rates will have to be applied over several hundreds of years to predict container lifetimes; therefore, the usefulness of the test results will depend strongly on a knowledge of the precision of those results.

In Sec. 3.9.1.4, the text states that metal penetration should be determined approximately monthly during the tests. However, in Sec. 3.9.2.1, it states that metal penetration, which will ultimately be used as a measure of the corrosion rate, is to be measured by removing the oxide film and weighing the sample, a procedure that disrupts the corrosion process. The relationship between the suggested monthly determinations of metal penetration and the proposed 3-month, 6-month, 1-year, 2-year, and 5-year test periods should be explained. The panel also suggests that instantaneous corrosion rates are to be determined from monitoring the evolution of hydrogen gas (Sec. 3.9.2.3). This approach is valid only if the reduction of hydrogen ions or water is the cathodic reaction. Hence, the approach is not likely to be applicable in the case of oxygenated brines. Also, implementation will be very difficult because hydrogen tends to diffuse through vessel materials. It is unlikely that gas evolution can be reliably measured over a five-year period.

As pointed out in Sec. 3.9.1.2, the chemical composition of brine in the vicinity of the test sample may vary during the course of a corrosion test because reactants are consumed and corrosion products are liberated. How the panel intends to deal with this complication is unclear. Flowing or recirculating systems are mentioned as a way of minimizing changes in brine composition, but the desirability of this approach is not discussed. The feasibility of maintaining 0-ppm-oxygen conditions is also not discussed. Apparently, earlier tests by Westerman used oxygen concentrations of 50.0 ppb. Whether this value is low enough to be considered zero is unclear. Finally, to ensure successful long-term tests, additional consideration must be given to the method of controlling magnesium and oxygen concentrations. If a flowing system is chosen as a means of control, backup and safeguard systems will be needed to ensure that long-term tests are not prematurely terminated by equipment failure.

Hydrogen gas, possibly in large amounts, will be produced during the tests. The treatment of this gas during the tests should be discussed more thoroughly. Will it be bled off and monitored as an indication of corrosion rate, or will it be allowed to build up and perhaps affect corrosion or brine chemistry?

The hydrogen ion activity (pH) is to be determined at ambient temperatures and pressures before and after each test. Given that pH is known to have a strong effect on corrosion rates, particularly at low values, more consideration should be given to this variable. Although pH measurements at ambient temperatures may be useful in a qualitative sense, they are of little value for predictive purposes because the pH at elevated temperatures can be vastly different from, and not related simply to, the value measured at ambient temperature. An elaborate chemical speciation model would have to be used to relate the measured pH to the pH that existed under experimental conditions. As an alternative, consideration should be given to measuring pH at the temperatures of interest using a specially designed probe such as a $ZrO_2(Y_2O_3)/HgO$, Hg probe.

The discussion in Secs. 3.9.2.5 and 3.9.2.6 of how electric potentials are to be monitored during the tests is very brief and somewhat misleading. To measure changes in redox or corrosion potential as the system evolves, careful consideration must be given to selecting proper reference electrodes (i.e., ones that do not change with the composition of the system). Because such electrodes are available, proper electrochemical monitoring of the system can and should be carried out.

2.7 IMPLEMENTATION PLAN

Section 4.0 describes four sets of supplementary tests designed to investigate the potential effects on uniform corrosion of several factors not included in the main factorial test matrix. Many of the factors considered in the supplementary tests were apparently discounted early on in the selection of dominant factors. However, from the discussion in Sec. 4.0, it appears that many questions as to dominant factors remain and that they should have been discussed in a more straightforward manner in association with selection of dominant factors.

The panel explicitly states that the results of these supplementary tests could have a profound effect on the design and implementation of the main tests. Because of this possibility, the panel should explain and justify the apparently secondary role played by these supplementary tests in the total test design. Some of these supplementary tests might better be scheduled early in the test program so that their results could be used to refine and redirect subsequent tests. This approach seems especially prudent in light of the present lack of knowledge concerning uniform corrosion of low-carbon steel under repository conditions.

A sequential implementation plan for the main tests is recommended in Sec. 3.11. Because of the panel's stated lack of confidence in the reliability of the predicted results of these tests and because of its expectation that a large number of long-term tests will be needed, the implementation plan is a very important part of the overall test design. The same is true of the implementation plan for the supplemental tests. Critical decisions involving development of these implementation plans were apparently treated in a seemingly ad hoc fashion. These decisions are not sufficiently well justified technically. The decision process used to arrive at the recommended implementation plan for the main tests is not discussed, and no implementation plan is given for the supplementary tests. Moreover, the decision criteria that were used are not identified so that their reasonableness can be judged. The tradeoffs made among the criteria, how expert judgments were used, and how consensus was reached are important points that should also be treated more fully.

Because the tests are being planned without complete knowledge of final waste package and repository designs, changes in disposal container material and expected repository conditions may occur during the five-year period of the tests. Also, because the predictions of the expected corrosion rates are not believed to be reliable, unexpected test results may require that the test plan be modified. Therefore, some consideration should be given to the flexibility of the overall test design and the criteria that should be used to identify a need for changing the test design.

From a decision-making perspective, the implementation plan should be an integral part of the overall decision problem. One possibility would be to perform a limited sequence of tests to gather information before addressing whether the full factorial design and the supplementary tests are needed. It might have been useful to have asked the panel to design alternative test plans for gaining near-term information (i.e., for reducing uncertainty). The decision problem could then focus on choosing the near-term test plan that would provide the best base of information for making technically defensible judgments concerning possible reduction of the test matrix. Such an approach would more completely support the objective of the test program.

2.8 USE OF AVAILABLE INFORMATION, DATA, AND OUTSIDE EXPERTISE

The report does not adequately document the expertise of the panel and the effort put into developing the proposed test design. In particular, the extent to which the panel made use of all available data and outside expertise is not well documented. Also, the concerns identified in Secs. 2.1-2.7 of this report indicate that certain important aspects of the test design are not addressed. Input from outside the panel may be needed for better identification of expected ranges of environmental conditions for the disposal containers in a repository setting. Also, the panel's confidence in the consensus corrosion rates might have been increased through more extensive review of the literature on the corrosion of carbon steel and similar materials in chloride solutions and other corrosive media. All available data should have been discussed by the panel as a whole before panelists made their individual predictions. All of the data should have been available to everyone.

The corrosion of metals is a very complex process involving many mass-transfer, charge-transfer, adsorption, film-growth, and chemical-reaction phenomena, most of which are time, temperature, and concentration dependent. It is not surprising, then, that the existing data points are highly scattered. Previous studies may simply have failed to control all the variables that determine the rate of attack. The predictions of the individual panelists in Tables 3-1 and 3-2 clearly reflect this scatter.

Corrosion theory is not sufficiently well developed to predict the complex dependencies of corrosion rate on the various controlling parameters. Accordingly, the panel's decision to adopt an empirical approach to the problem is probably prudent at this time. However, the success of this approach will rely very heavily on correctly identifying the most important environmental parameters affecting the corrosion rate. The panel relied upon highly unreliable data from the literature to do this. As a result, the danger exists that some other parameter not studied in the previous work may have a pronounced effect on the corrosion rate. The selection of potential controlling factors for the tests is therefore an especially critical part of the test design process. Also, because of the large number and long duration of the proposed tests, development of a test implementation plan becomes a second critical part of the test design process. Neither of these aspects of the design process is adequately addressed in O/TM-71.

2.9 OTHER CONCERNS

Several additional concerns identified during the review of O/TM-71 are discussed briefly below.

The consensus corrosion rates are presented and discussed briefly in Sec. 3.6. Other than a statement that the panel has very little confidence in the predicted rates, the text says little about what can be learned from the results. As actual data gradually replace these predictions, a fundamental understanding should be gained about the effects of the individual factors controlling corrosion. Therefore, more consideration should be given to the form in which the corrosion rates are presented, to the types of conclusions that can be drawn, and to the relationship of these conclusions to basic physical and chemical principles. For example, it may be important to know how the corrosion rate changes when one of the controlling factors changes from its lower to its upper limit. Tables that present the change in the corrosion rate (expressed as the ratio of corrosion rates) when one controlling factor changes while the others remain fixed at the various combinations of their bounding values could help identify the relative importance of individual controlling factors under specific conditions.

At the very end of Sec. 4.0, the text mentions that the interaction of magnesium ions with the corroding surface of mild steel may form a complex iron-magnesium-manganese hydroxide (amakinite) instead of magnetite, with a resulting corrosion rate approximately 20 times higher than when magnetite forms. The panel acknowledges the importance of understanding the detailed mechanism of this interaction and recommends that a corrosion research program be undertaken. These comments appear to have been tacked on to the end of the section as an afterthought. If the panel considers an understanding of this mechanism to be important, and if the accompanying corrosion rates are indeed 20 times higher that those associated with formation of magnetite, more consideration should be given to the need for additional research than is expressed in the two or three sentences at the end of Sec. 4.0.

Appendix D describes a technique for determining the main effects and interactions of the controlling factors by means of fitting a series of standard orthogonal polynomials to corrosion rate data. The technique is similar to that indicated in ONWI-501, although the ONWI-501 procedure is not referenced. Generally speaking, App. D is poorly written and would benefit from references to standard statistical texts for an explanation of the details of the procedure. More importantly, the purpose and utility of the technique seem to be incorrectly stated. It is claimed on page 93 that the method is intended to serve as an example of an approach that might be used to reduce the number of tests. However, it is not clear how the panel intends for this technique to be applied once some real data (short of the full 2x5x5 matrix) become available. The interpolation scheme used will strongly affect the results of applying the technique. Therefore, if an interpolation scheme is to be used, it must be based on an understanding of the fundamentals of corrosion physics and chemistry. Although the technique could be used to identify main effects and interactions and to develop an empirical model for uniform corrosion, it is not clear how the technique could be used to "prune" the test matrix without also having the additional knowledge necessary to improve the interpolation scheme. If the panel intends to use the technique described in App. D to "prune" the test matrix, this application of the method should be more clearly described.

3 PAGE-BY-PAGE COMMENTARY

Page	Line(s)	Comment
xi	6-13	Figures 3-2 and 3-4 and Figs. 3-3 and 3-5 have identical captions. The differences between the figures (linear vs. logarithmic scales) should be mentioned.
1	3-6	The terms "uniform corrosion" and "general corrosion" are both used. If they refer to the same process, the same term should be used for consistency. The meaning of the term "general corrosion conditions" should be clarified.
1	9	The comma after "system" should be deleted.
1	23	It is not appropriate to "compromise" *necessary* scientific objectives if these objectives are needed to prepare a defensible license application. The sentence should be reworded.
1	29	The term "accelerated test design" is used here for the first time; therefore, the term should be defined. Also, this document does not deal directly with accelerated testing which, according to ONWI-501, involves "over stressing" during testing and extrapolation to actual repository conditions. This point should be clarified.
1	39	The original testing program (and the present test program) did not deal directly with "life" testing as such, only with the determination of uniform corrosion rates under various environmental conditions. This point should be clarified.
2	17-24	A one-to-one correspondence does not exist between the portions of the waste package shown in Fig. 1-1 and those discussed in the text. For example, the text mentions backfill materials and emplacement hole liners, and the figure does not show these features. Conversely, the figure shows assembly gaps, which are not discussed in the text. The text and the figure should be made to agree.
5	22	The line should be changed to read "technical evidence *as* interpreted."
5	29-31	The test program discussed in this document will provide corrosion rates as a function of a range of expected environmental conditions. Much additional information will be needed to estimate container life expectancy in an actual repository. In addition, the test program assumes a container of low-carbon steel as well as uniform corrosion. Also, because accelerated testing is not used, the test program assumes that corrosion rates will reach a steady state within the five-year test period. The fact that the test results will not lead directly to estimates of container life should be pointed out.

Page	Line(s)	Comment
6	11-13	The "early corrosion studies" and "later studies" should be referenced.
6	13-14	The specific types of brine (intrusion and inclusion), mentioned here for the first time, should be defined and characterized.
6	21-24	References should be given to support the statement that the forms of nonuniform corrosion mentioned are "not inevitable."
6	26-27	Because readers may not be familiar with the results of the "Westerman et al., 1985" report at this point, the statement that "uniform corrosion has been the only significant degradation mode observed" should be more carefully supported.
6	32-33	A reference should be given for the 10-15-cm container thickness mentioned.
6	36-39	If the judgment referred to is that of the panel, a statement to this effect should be added; if it is based on the literature, a reference should be given.
7	4	Numerous terms such as "factors having significant influence," "dominant factors," "critical factors," "controlling factors," "factors," "experimental factors," "stresses," and "controlled variables" are used throughout the document to describe a similar concept. It would be preferable to be consistent and stay with one or two carefully selected terms.
7	7-8	Justification is needed for selecting only these two components for the text matrix. The following questions should be answered by this justification. Do the two components come from ONWI-501? Are there other possible components? How are the dominant factors identified? Does the primary component have to be a factorial matrix? (If certain values of one factor are not expected to occur in conjunction with certain values of other factors, then a complete factorial matrix may not be required.)
7	16-17	The use of "unlimited brines" in the tests should be justified. Also, the precise meaning of the term "unlimited brine" in this context should be stated.
7	21	The comma between the words "layer" and "composition" should be removed.
7	25	It should be emphasized that a predictive model for the corrosion rate *as a function of time* is needed.

Page	Line(s)	Comment
7	25-27	It seems evident that the corrosion rate at any given time may depend on the previous history of the material. For example, a corrosion-products layer may develop as a result of exposure to different, earlier environmental conditions. This dependence could affect the ability to integrate corrosion rates over time under changing environmental conditions. This possibility and its effect, if any, on the experimental test design should be discussed.
7	30-41	A portion of ONWI-501 deals with accelerated life-cycle testing. Because O/TM-71 does not appear to deal with accelerated life-cycle testing, the text should mention that the panel has not adopted that as its goal.
7	39	The words "numerical estimates" should be replaced with "numerical estimates of corrosion rates."
7	41	The words "hierarchical trees" should be replaced with "hierarchical trees to graphically display the anticipated interactions among the factors and the corrosion rates."
8	8-9	The terms "main effects" and "interactions" are used for the first time here. Because these terms have specific meanings with respect to the methodology of ONWI-501 and the methodology used in this document, they should be defined here.
8	10-11	The term "adequacy of the experimental design" is used. The criteria used to determine "adequacy" should be described.
8	20-27	Further discussion would be useful on the selection of the expert panel and its composition because the judgments of the panelists provide the basis for developing the test program. The one-page résumés in App. A are very helpful for highlighting the credentials of the participants, but potential biases (e.g., cognitive biases that may adversely affect judgments) and measures taken to mitigate their effects should be discussed.
11	5-7	In addition to satisfying "data-generation requirements," the test design must address the needs of the waste-package design and waste-package performance assessment aspects of the Salt Repository Project. This point should be clarified.
11	17-18	The overall objective of ONWI-501 has been modified here from what ONWI-501 says in its abstract. Again, it should be clear that O/TM-71 does not involve "accelerated life tests."

Page	Line(s)	Comment
12	2-6	Obtaining "consensus test design" by eliminating the "weaker and less-substantiated inputs to the design process" seems somewhat inappropriate given the concerns of the panelists about the lack of available data upon which to base predictions and the fact that judgments are not represented probabilistically. In view of the level of uncertainty, the question of how the inputs were determined to be "weak and less substantiated" should be addressed.
12	9-12	The text should note that hierarchical tree can also be used to add tests where necessary.
12	16-18	The text should again mention that the "accelerated life testing" of ONWI-501 was not adopted for this proposed test design.
12	37-39	The method used to determine the number of required replicates should be described.
13	2-16	The conceptual model to be used to determine package life should be more clearly described. For example, the general approach that might be used to integrate over varying environmental conditions and corrosion rates should be discussed. Sketches of expected variations in environmental conditions and corrosion rates with time might help clarify this integration.
13	8-10	The first bullet should be replaced by: "A quantitative determination of uniform corrosion rates as functions of environmental factors or stresses such as temperature, brine composition, and oxygen concentration." The specific "stresses" that are expected to have an important effect on corrosion rates have not yet been identified in the document.
13	15	The word "integration" should be replaced with "prediction."
13	37-40	The comment about "the need to have a full understanding of this topic" is not clear and could be misconstrued. Rewriting is necessary.
13	35-37	The second meeting is said to have been of two days' duration, which does not agree with Table 2-1. This discrepancy should be resolved.
15	8-10	The technique used to obtain consensus positions should be described.
15	11-21	Any discussion by the panel as to why "accelerated life testing" as presented in ONWI-501 was rejected as a means of approaching the uniform corrosion problem should be included here.

Page	Line(s)	Comment
15	18-19	The text should discuss the justification for restricting consideration to factorial matrices and the advantages of working with factorial matrices. Also, the meaning of the term "'dominant' factor space" is not clear at this point in the document. The text should at least state that the "dominant" factors must be identified by the panel.
15	22-35	The panel decided that, compared with tests in seawater, the conditions in a repository will cause a steady state corrosion rate to be reached within several months (as opposed to two years) and that the time dependency should be taken as 1.0 (as opposed to 0.76). Both of these assumptions should be justified.
15	25	A reference should be given for the corrosion tests in geothermal environments.
15	32-35	The text states that the time exponent of 0.76 used in the Westinghouse report was derived from the seawater data. However, in the first part of the same paragraph, the text states that the seawater results showed that the corrosion rate reached steady state within two years. This finding appears to be consistent with a time exponent of unity rather than 0.76. The apparent discrepancy should be resolved.
15	36	The words "to the estimated test results developed by the panel" should be inserted after "predictive model fitting."
15	40	The word "data" should be replaced with "estimated test results developed by the panel."
15	40-43	It is not clear that fitting a set of orthogonal polynomials checks "the statistical validity of the data." The panel should define what it means by "statistical validity."
15	43-45	The text states that the polynomial models may be "uncertain outside this [factor] space." It is not clear whether *this space* refers to values of the factors beyond the bounds set by the panel based on expected repository conditions or whether *this space* refers to any point, even those within the bounds, not specifically addressed by the estimates of the panel.
16	12-13	The discussion of the brine environment is limited to oxygen and magnesium content. Reasons should be given for ignoring other brine constituents.

Page	Line(s)	Comment
16	19-26	The text does not prove that inclusion-brine conditions lead to low-oxygen brines. Residual oxygen in the gaps around the waste packages might contribute to the oxygen content of inclusion brines. This possibility should be discussed.
16	27-36	A scenario can be envisioned in which brine periodically reaches the waste package throughout its life. The circumstances under which this scenario could be worse than a continuous, infinite supply of brine should be considered. For example, changes in brine composition in the case of limited brine could result in faster corrosion rates.
17	10	This use of the term "'fundamental variables'" is confusing. The term "secondary variables" might be better.
17	25	The term "'primary variable'" is used here for the first time. If yet another term must be introduced, it should be defined; if not, it should be eliminated.
17	26	The term "fundamental variables" is used here without quotes to apparently mean the experimentally controllable factors rather than the variables that are fundamental in a physicochemical sense. As previously noted, more care should be taken in selecting and using such terms. In addition, the definition of "fundamental variables" suggested here is circular and weak. It should be expanded upon.
17	28-30	The reasons given for eliminating the effects of metal aging and pressure are cursory. Supporting references should be provided.
17	30-32	Scientific reasons should be given for why system flow rates and the presence or absence of a solid phase will not limit the usefulness of the test results. In particular, the dismissal of solid-phase effects in this paragraph does not seem consistent with the discussion in Sec. 4.0 of the potential effects of a solid salt phase on corrosion rates.
17	32-33	The corrosion product film thickness is referred to as a "primary measured variable" (another new term). A reason should be given for why the variable is considered "primary" and what the adjective "primary" implies.
17	34-39	The effect of gamma radiation on the corrosion of low-carbon steels is presented here simply as a matter of exceeding a threshold (3000 rads per hour). It is not clear that the issue of radiation effects can be handled that simply. Long-term radiation effects on low-carbon steel may have chronic effects on corrosion rates. Specific references to support the threshold nature of radiation effects should be cited.

Page	Line(s)	Comment
18	21	One of the fundamental variables is referred to as "oxygen fugacity" here and "oxygen concentration" in the previous paragraph. If the terminology needs to be changed at this point, an explanation is needed; if not, the change should be avoided.
18	31	The word "'stress'" should be changed to "the effect on corrosion rate."
19	9-12	A reference is needed for the expected effect of temperature on magnesium concentration and thus pH.
19	13-20	References are needed to support the magnesium concentration limits discussed.
21	1-6	The availability of oxygen in the repository environment should be discussed to provide a basis for predicting brine oxygen concentrations.
21	7-27	At least a hypothetical curve of corrosion rate versus time for expected repository conditions and expected test conditions should be provided. Even a hypothetical curve of this type would make selection of time periods clearer. Moreover, it would provide a framework against which to judge the results of early experiments.
21	17-19	A supporting reference is needed for the statement that corrosion rates do not decrease for about six months.
21	20-22	Supporting references should be supplied for the statement that the panel felt that five-year experiments are necessary to reach steady state conditions.
21	39-42	An expanded explanation should be provided of why all of the experts except Lee and Westerman relied only on the Pacific Northwest Laboratories data for predicting corrosion rates. A key question is whether the data sources were discussed before the experts were asked to make predictions. It is extremely important to clarify this point in light of the fact that Ballinger, Cunnane, and Kuhn all withdrew their predicted corrosion rates corresponding to high-oxygen, low-magnesium conditions, deferring to Lee and Westerman whose judgments indicated a dominance of temperature over magnesium concentration and oxygen fugacity. As Tables 3-1 and 3-2 show, the resultant "consensus corrosion rates" for these sets of conditions were greatly affected by the withdrawal of the estimates by the three experts. The technical arguments advanced by Lee and Westerman, as well as any new data that may have been used, should be more fully described.

Page	Line(s)	Comment
23	3	The stated lack of "credible models for a repository environment" weakens the rationale for the test design. The effect this lack of input may have on the test design should be discussed.
23	15-25	This explanation of how the hierarchical trees are constructed is very brief. In particular, the discussion of orthogonal polynomials is not clear. A reference to App. D is indicated, although the explanation there is not very clear either. Moreover, because ONWI-501 does not use the term "orthogonal polynomials" (although that is apparently what is used), the discussion of determining dominant factors by means of orthogonal polynomial analysis should be linked to the work in App. A of ONWI-501.
24	1-4	One appreciates the candor of the panel with regard to its "lack of confidence in the predicted corrosion rates and in the tree structure," but one feels that the panelists proceeded in spite of this lack of confidence. It might have been better to stop at this point and to design the tests without further reference to ONWI-501.
24	15	It is not obvious who "they" are. If "they" are the members of the panel besides Westerman and Lee, this fact should be stated more clearly.
24	19	The units for the 0.0005 value should be millimeters per year.
24	29-30	The method of averaging the corrosion rates should be explained.
24	32-33	The average value of 1.125 mm/yr for "mean" values of the temperature, oxygen concentration, and magnesium concentration ranges does not agree with the value given in Figs. 3-2 and 3-4 (1.145 mm/yr). Also, the "mean" aspect of the factors should be explained.
24	35	The value of 1.92 mm/yr does not agree with the value given in Figs. 3-2 and 3-4 (1.955 mm/yr).
25		Lines 5 and 7 of Table 3-2 show that even though individual panelists estimated that the higher magnesium concentration would result in the same or higher corrosion rate compared with the lower magnesium concentration (all other factors being equal), the consensus corrosion rates show the opposite trend. Therefore, the consensus corrosion rates apparently do *not* reflect the predictions of the panelists. This conflict should be resolved or explained. Lines 13 and 15 of the table show the same discrepancy.

Page	Line(s)	Comment
27		There appears to be an arithmetic error in two of the values of average corrosion rates given on the tree. At the top, the value 0.8917 should be 0.89125. And, at the high-temperature branch of the next level down, the value 1.527 should be 1.5225. The same numbers also appear in Fig. 3-5.
28	38-42	The conclusion drawn about the unreliability of the predicted corrosion rates and the panel's refusal to rely on the consensus tree ought to be mentioned in the abstract and Sec. 1.0. That is, the fact that the ONWI-501 methodology was essentially abandoned at this point in the planning should be mentioned up front.
31	11	A reason should be given as to why no additional levels of oxygen concentration were considered necessary at this time.
31	16-19	It is not clear what the "analysis of the state of the existing low-carbon steel data base for repository relevant conditions" is or where it is reported. This "analysis" should be discussed or referenced here. If this analysis was known to the panelists at the beginning of this exercise (which it seems to have been), the panel might have been able to move to this point immediately.
32	15-17	A reference is needed to support the statement that a sharp increase in the corrosion rate in high-magnesium brines is expected near 170-200°C.
32	21-30	Oxygen levels should be given for the Sandia National Laboratory studies of mild steel.
33	11-14	The text does not state whether magnesium alone results in corrosion products or whether other constituents of the brine may contribute to corrosion products and should be considered in terms of brine chemistry. The effect of brine composition on corrosion (beyond magnesium concentration) should be discussed in more detail.
33	25	The panel should comment on why it believed a geometric series was more appropriate than an algebraic series.
34	21-23	The basis for the temperature control range (±5°C) should be mentioned. A reference should be cited if the range is not based on the experience of the panelists.
34	25-28	The composition of brine may also vary in a repository setting. Changing brine composition caused by metal dissolution and liberation of corrosion products should be considered as a factor that could influence subsequent corrosion.

Page	Line(s)	Comment
34	28-31	Whether to refresh specimen surfaces is left in the context of "if desired." The panel should recommend an approach and show how it is conservative for the purpose of predicting corrosion rates. Or, the reasons for leaving this unspecified should be discussed.
35	2-15	The feasibility of maintaining 0-ppm-oxygen conditions is not discussed. The information about the supplementary tests includes a statement that Westerman has used 50.0 ppb oxygen in his experiments. The text should clarify whether this value is low enough to be considered "zero."
35	7-13	The discussion of flowing or static brine systems is confusing, and again the panel does not recommend an appropriate approach for the test. In particular, the sentence beginning "The former method utilizes. . ." should be reworded to increase its clarity.
35	23-24	A frequency for the measurement of oxygen concentration should be included here.
35	24	The procedure for measuring metal penetration described in Sec. 3.9.2.1 involves removing the oxide film and thus disrupting the corrosion process. The intent of the panel in suggesting that metal penetration data should be obtained monthly should be explained in light of the fact that three-month, six-month, one-year, two-year, and five-year tests are suggested in Sec. 3.8.2.3.
35	38-39	The precision of corrosion rate determinations must depend somewhat on sample size. Therefore, the sample size envisioned for these tests should be given. Also, the text states that "the precision of corrosion rate determinations between replicate specimens is typically within 20 percent." This measurement uncertainty should be treated in the methodological framework, along with the judgmental uncertainty about corrosion rates.
36	7-13	Section 3.9.2.3 seems to indicate that instantaneous corrosion rates as a function of time can be obtained from these experiments. If so, the primary reason for suggesting a series of three-month, six-month, one-year, two-year, and five-year tests appears to be to obtain information about specific corrosion products at these times and to verify integrated corrosion rates by the weight-change method. This point should be clarified and discussed in more detail. In addition, the way in which evolution of hydrogen gas is to be handled experimentally should be discussed. The text should indicate whether hydrogen will be bled off and monitored as an indication of corrosion rate or whether it will be allowed to build up and perhaps affect the corrosion process or the chemical composition of the brine. Finally, the relationship between pH and evolution of hydrogen gas should be discussed.

Page	Line(s)	Comment
36	15-22	The correlation between pH at ambient temperature and pH at high temperature should be discussed. This relationship will be needed if a mechanism for the effect of pH on corrosion is to be determined.
37	3	Replicate samples are mentioned for the first time here. Reasons should be given for selecting five replications at each test condition.
37	7-8	If 250 specimens are required at each of the five time levels, 1250 tests must be conducted. As written, the text is unclear as to whether the total number of tests is 250 or 1250.
37	10-11	Procedures for running the tests are not discussed in Sec. 3.9. Either the test procedures should be described in Sec. 3.9, or this sentence should be changed to reflect what is actually in that section.
38	18-37	No explicit justification is given for the test matrix for the five-year tests or for the amended test matrix for the other time periods. One would guess that the justification is related to the large increases in facilities and personnel over current levels required to carry out the full matrix of 1250 tests. Explicit justification should be given for the selection of these reduced test matrices. The justification should consider at least the following points. The suggested initial five-year test matrix contains only three levels of magnesium concentration and does not include the lower bound (100 ppm). Reasons should be given for selecting the magnesium concentration levels for "pruning" and for selecting the three levels that were retained. The initial test matrices for the other time levels involve "pruning" the temperature levels as well as the magnesium concentration levels. Again, the reasoning used to select these temperature levels (and exclude the 250°C upper bound) should be given. Finally, consideration should be given to an implementation plan for the 3-, 6-, 12-, and 24-month tests.
39	7-9	Nowhere in App. D, or elsewhere in the document, does the text say how one can determine "adequacy" of testing as indicated here. This statement should be clarified, and the precise meaning intended for the word "adequacy" should be given.
39	10-14	The use that will be made of the "predictions. . .of the corrosion rates expected to be measured at a future time" should be described.
39	16	The word "correctly" is inappropriate and should be deleted.

Page	Line(s)	Comment
39	16-33	Another deficiency in the ONWI-501 methodology is that it lacks a prescription for accelerated life testing. If accelerated life testing was not considered by the panel because such testing is not adequately discussed in ONWI-501, this deficiency in the ONWI-501 methodology should be discussed here.
41	10	The primary tests are to use five replicates. The number of replicates for the supplementary tests should be specified.
41	28	The synthetic brines PBB1 and PBB3 are referred to here for the first time. Because these synthetic brines are to be used in the supplementary tests, their composition, their relationship to the brines used for the main test matrix, and the repository conditions they are supposed to represent should be discussed here.
42	1-17	The reasons for selecting these temperatures (150°C and 200°C) for the "solid-salt phase" tests should be explained. It appears that the second set of tests at 200°C constitutes new tests and that the first set at 150°C has already been completed, but the text is not explicit. Also, the relevance of 50 ppb oxygen levels in these two tests and the relationship to the original test matrix values of 0 ppm and 1.5 ppm should be discussed.
42	9-11	The text states that an additional three-month test will be conducted in a "slowly refreshing autoclave." However, in the tests described directly below this statement, both three- and six-month tests are specified. This apparent discrepancy should be clarified.
42	19-34	The text should explain how the tests can be carried out to account for the release of hydrogen gas with time.
42	22	A reference should be given for the value of the expected lithostatic pressure mentioned. Also, although metric units are generally used in the memorandum, units such as "psi" and "mil/yr" occasionally appear. Metric units should be used throughout the report, with other units indicated parenthetically if necessary because of common usage or for clarity.
42	28-31	The reason for specifying a "welded static reaction vessel" over seamless vessel should be discussed.
42	36-41	Some justification is needed for the selected temperature and oxygen concentration levels for these hydrogen-pressure tests, as well as for the "microstructure" tests on page 43.
42	40	The label on the oxygen concentration should most likely be parts per billion and not parts per million.

Page	Line(s)	Comment
43	26-32	More justification is needed for suggesting a magnesium concentration of 2 x 10^5 ppm. It is not apparent that increasing the magnesium concentration by a factor of two over the maximum in the main test matrix (which already covers three orders of magnitude) is likely to provide important additional information on the effects of magnesium. If the magnesium concentration effect is expected to be that nonlinear, then the concentration intervals chosen for the test matrix should be adjusted to accommodate this fact.
44	1-12	This paragraph on the interaction of magnesium ions with the corroding surface of mild steels seems completely disconnected from the rest of Sec. 4.0. The paragraph does not seem to describe another supplementary test. If the high corrosion rates resulting from the formation of amakinite are considered to be important, more consideration should be given to the need for additional research than the two or three sentences at the end of this section.
45	3-10	While it may be true that the Sandia National Laboratory tests "are not directly equivalent to [the] tests contained in the test matrix presented in this report," the results may be generally applicable, even though the Sandia tests were short term. More should be said about these results.
46	8	The issue of overlapping tests seems less important than relating the results of the tests to the proposed test matrix. One presumes that these data, or some form of them, were the Pacific Northwest Laboratories data available to the panelists for their estimates of corrosion rates.
47	10-13	The conclusion that "the recommended matrix. . .is expected to demand a significant increase in the facility and personnel over the current levels" may be true. It seems reasonable to expect that a major test matrix such as the one proposed would represent a significant increase over the apparently small present effort. However, this expectation should be supported. There has been no discussion to this point in the report about the levels of activity in the current program against which to judge any increases.
47	22-27	Reviewers had no quarrel with using data from early tests as a guide in reevaluating the planned test matrix. However, it is not clear that the technique demonstrated in App. D, or any of the other approaches put forward in the report, provides a basis for such an evaluation. Moreover, no procedure is provided for incorporating the results of the supplementary tests into modifications of the planned test matrix. The procedure the panel expects to follow when reevaluating the test matrix as new data become available should be described more clearly.

Page	Line(s)	Comment
47	28-29	Although "an expert team approach" was used, the approach described in ONWI-501 was not used. As indicated in lines 44-45, "the results of the analysis [suggested by ONWI-501] did not play a significant role in the [formulation of the] recommended test matrix."
48	3-5	The connection between the test matrix and the Waste Package Program Plan seems to be reversed. The Waste Package Program Plan should drive the development of the test matrix, not the other way around.
50	1-4	The "Westerman et al., 1985" report is not yet published. Reference citations should state if a report is unpublished or not readily available for some other reason.
69	20-26	The units should be given for the coefficients in the two equations.
81	13-14	The reason why data from all seven alloys rather than just the data from A216 cast steel are used to make the predictions should be discussed, as well as any expected influence the choice might have on the predictions.
81	21-28	The activation energies are given in units of "kcal/mole." The units should probably be "cal/mole."
86	11-12	"Splitting the difference" is not clear in this context of power relationships. The sentence should be reworded.
87	11-15	The use of this equation should be explained in light of the fact that the panel agreed that $t^{1.0}$ is more reasonable.
87	19-21	A more detailed justification is needed of the factor-of-10 reduction in corrosion rate data.
91	18	The phrase "fitting standard orthogonal polynomials" should be replaced with "fitting a set of standard orthonormal polynomials." Normalized polynomials were used to obtain the coefficients in Table D-2 rather than rationalized polynomials, which have traditionally been used when such fitting procedures were done by hand rather than by electronic computers.
91	19	The word "estimated" should be replaced by "evaluated," unless "estimated" is intended to imply that the resulting coefficients are estimates because they are based on predicted and interpolated values rather than actual data.
91	20	The phrase "terms in the" should be removed.

Page	Line(s)	Comment
91	20-22	A reference should be given for those not familiar with the details of this type of statistical procedure.
91	37-38	It appears that the entity "associated term in the polynomial" refers to the highest order term in the particular polynomial. This point should be clarified for those not familiar with the details of this procedure of fitting a set of "data" points to a corresponding complete set of orthogonal polynomials.
92	4-7	This very important point should be expanded upon. Not only must the responses (corrosion rates) predicted by the experts at the end points (bounds) of the parameter (experimentally controlled variable) space be valid, but enough must be known about the response interior to the parameter space so that the higher-order main effects and interactions are reasonably well represented.
92	12-19	The text should clarify whether the present interpolation scheme actually "reflect[s] expected changes in the dominant corrosion mechanisms" based on the expert opinion of the panel or whether it is just a convenience for this example of the analytical method. The text should mention that the interpolation scheme is based on geometric means.
92	24-25	The coefficients (computed magnitudes) of Table D-2 are not least-squares estimates of the coefficients. They are exact values (based on the 50 "data" points) determined by fitting 50 coefficients to 50 corrosion rates. In other words, the resulting function formed from the 50 coefficients and the 50 polynomials exactly reproduces the 50 "data" points.
92	27-32	The cubic effect of temperature (1.37 mm/yr) has been omitted from the list of the eight largest effects.
92	33-34	How the $2 \times 3 \times 4$ reduced factorial design was selected should be described in more detail.
92	35	The phrase "fitted polynomial coefficients" should be replaced with "fitted polynomial coefficients from Table D-2."
92	39-41	The text should point out that the resulting fit (corresponding to Table D-3) to the subset (24 members) of the original complete set of 50 orthonormal polynomials represents a least-squares fit to the original 50 "data" points in the traditional sense.

Page	Line(s)	Comment
92	39-41	Even though the selected 24 terms account for about 98% of the variance of the original 50 "data" points, the remaining variance may not be negligible in all regions of the parameter space. The sum of the squares of the deviations of the 24-parameter polynomial least-squares fit from the original 50 "data" points is given by the sum of the squares of the 26 coefficients (computed magnitudes of Table D-2) that have been omitted. This sum amounts to 1.2629 $(mm/yr)^2$. Therefore, the RMS (root-mean-square) deviation of the 50 "data" points from the 24-parameter polynomial fit will be 0.159 mm/yr (the square root of 1.2629/50). While this amount corresponds to only 3.90% of the maximum estimated corrosion rate (4.08 mm/yr), it corresponds to 13.4% of the RMS corrosion rate (1.183 mm/yr, based on all 50 "data" points), 19.8% of the average corrosion rate (0.805 mm/yr, based on all 50 "data" points), and 1590% of the minimum predicted corrosion rate (0.01 mm/yr). To assess whether these potential "errors" are acceptable, one must first determine how the corrosion rates to be predicted by this empirical polynomial model will enter into the prediction of container lifetime in a salt repository. If it turns out that relative uncertainties (percentages) are more important than absolute uncertainties, it might be best to fit the polynomial model to some function of the corrosion rate (such as the logarithm of the corrosion rate) rather than to the corrosion rate itself.
93		The interpolated corrosion rate for test 7 should be 0.09672 mm/yr. The corrosion rate for tests 28 and 29 should be 1.16962 mm/yr. The comma in the corrosion rate for test 33 should be a decimal point. The experimental conditions for tests 49 and 50 should be (1,4,3) and (1,4,4), respectively.
95		The interaction for line 35 should include the fourth rather than the second power of temperature.
96		The variance component for line 1 should be 46.3%. Note that this constant term can be calculated directly from the original 50 corrosion-rate "data" points using $\{[\Sigma(CR)]^2/50\}/[\Sigma(CR)^2]$.
96		The variance component for line 14 is not consistent with Table D-2. If Table D-2 is correct, the value should be 0.4% or 0.5%, depending on how it is rounded off.
96		The total of the variance components (in terms of percent) can be calculated directly from the sum of the squares of the selected 24 computed magnitudes of Table D-2 divided by the sum of the squares of all 50 of the computed magnitudes of Table D-2, or 98.2%. The difference from the results of Table D-3 should be attributable only to rounding off.

Page	Line(s)	Comment
96		The interactions in lines 11, 12, 23, and 24 are not written in the same way as all the other main effects and interactions in Tables D-2 and D-3. This difference should be eliminated or explained.
97	3-4	The interpolation scheme described here is not the one described on page 92 or in Fig. D-1. This discrepancy should be eliminated. In addition, the formulas for the interpolation scheme are presented in an ambiguous and unclear format and should be revised.

REFERENCES

Bignold, G.J., R. Garnsey, and G.M.W. Mann, *High Temperature Aqueous Corrosion of Iron. Development of Theories of Equilibrium Solution Phase Transport through a Porous Oxide*, Corrosion Science, *12*:325-332 (1972).

Potter, E.C., and G.M.W. Mann, *The Fast Linear Growth of Magnetite on Mild Steel in High-Temperature Aqueous Conditions*, British Corrosion J., *1*:26-35 (1965).

Park, J.R., *The Mechanism of the Fast Growth of Magnetite on Carbon Steel under PRW Crevice Conditions*, Ph.D. dissertation, The Ohio State University, Columbus, Ohio (1983).

Thomas, R.E., and R.W. Cote, *Methodology for Predicting the Life of Waste-Package Materials and Components Using Multifactor Accelerated Life Tests*, ONWI-501, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, Ohio (Sept. 1983).

APPENDIX A

CORRESPONDENCE RELATED TO THE PEER REVIEW

Department of Energy
Chicago Operations Office
Salt Repository Project Office
505 King Avenue
Columbus, Ohio 43201-2693
Commercial (614) 424-5916
F.T.S. 976-5916

October 21, 1985

Wyman Harrison
EES-362
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Dear Dr. Harrison:

SUBJECT: REVIEW OF REPORT ENTITLED, "MULTIFACTOR TEST DESIGN TO INVESTIGATE UNIFORM CORROSION OF LOW-CARBON STEEL IN A NUCLEAR WASTE SALT REPOSITORY ENVIRONMENT"

SRPO requests that you form a peer review panel to review the attached subject report. The review should concentrate on the following:

- o The applications of methodology as described in Section 2.0
  - Applicability to the problem
  - Shortcomings/suggested improvements
- o The panel activities and results as described in Section 3.0
  - Assessment of controlling factors
  - Justifications
  - Feasibility of controlling and monitoring factor level
- o Supplementary test as described in Section 4.0
  - Applicability/importance
  - Any additional tests
- o Validity of the conclusions

If you have any questions concerning this matter, please contact Roger Wu of my staff.

Sincerely,

R.C. Wunderlich
Deputy Project Manager
Salt Repository Project Office

SRPO:KKW:max:9229B

Enclosure:
As Stated

ST# 037-86

ARGONNE NATIONAL LABORATORY
9700 SOUTH CASS AVENUE, ARGONNE, ILLINOIS 60439

TELEPHONE 312/972-3309

January 16, 1986

Mr. R.C. Wunderlich
Salt Repository Project Office
U.S. Department of Energy
505 King Avenue
Columbus, OH 43201

SUBJECT: PEER REVIEW OF ONWI TECHNICAL MEMORANDUM ENTITLED "MULTIFACTOR TEST DESIGN TO INVESTIGATE UNIFORM CORROSION OF LOW-CARBON STEEL IN A NUCLEAR WASTE SALT REPOSITORY ENVIRONMENT"

Dear Mr. Wunderlich:

As requested in your letter of October 21, 1985, Argonne National Laboratory conducted a peer review of the subject memorandum. The comments of the review panelists are synthesized in the revised review draft report entitled *Peer Review of the Office of Nuclear Waste Isolation's Draft Report on a Multifactor Test Design to Investigate Uniform Corrosion of Low-Carbon Steel.*

The several areas of concentration for the review mentioned in your letter are listed below in italics, followed by paragraphs that give the specific sections of the Argonne review report that address these areas.

- ***The applications of the methodology as described in Section 2.0.***
  - ***Applicability to the problem***
  - ***Shortcomings/suggested improvements***

  Section 2.1 points out that the relationship of the problem addressed by the expert panel (development of a corrosion test design) to the overall objectives of the waste package program of the Salt Repository Project is not adequately treated in the memorandum. Suggestions as to what is needed to establish this relationship are also included in this section. The degree to which the expert-panel methodology of ONWI-501 was followed during the test design process is discussed in Section 2.2, whereas reviewer concerns related to the consensus procedures used throughout the panel's deliberations are discussed in Section 2.3. The shortcomings of the methodology, especially the lack of treatment of uncertainty, are detailed in Section 2.4.

- ***The panel activities and results as described in Section 3.0.***
  - ***Assessment of controlling factors***
  - ***Justifications***
  - ***Feasibility of controlling and monitoring factor levels***

Concerns related to selection of controlling factors for the tests, the choice of experimental ranges for these factors, and the associated justifications supplied by the expert panel are discussed in the first half of Section 2.5. Section 2.6 comments on the limited treatment in the memorandum of how the proposed tests are to be conducted and of how certain factors that might affect the test results are to be handled, controlled, and monitored.

- ***Supplementary test as described in Section 4.0.***
  - Applicability/importance
  - Any additional tests

  The importance of the supplementary tests in establishing an implementation plan for the proposed tests in discussed in Section 2.7. Concerns raised by the reviewers related to potential controlling factors that were not included in the test design by the expert panel are presented in the second half of Section 2.5.

- ***Validity of the conclusions.***

  During the review, several major areas of concern were identified by the reviewers. The review panelists agreed that these areas, which are discussed in Section 2, are important to the credibility of the proposed test design and that they have not been adequately addressed in the memorandum. Until these areas are adequately addressed, it is not appropriate to judge the validity of the proposed test design.

Sincerely,

Wyman Harrison

Wyman Harrison
Energy and Environmental Systems Division

SRP:RP:WH:jp

ASDO-108
File No. 2.2.2.1

APPENDIX B

CONCURRENCE SHEET

APPENDIX B

CONCURRENCE SHEET

I concur that the Argonne National Laboratory report on ONWI's internal technical memorandum entitled *Multifactor Test Design to Investigate Uniform Corrosion of Low-Carbon Steel in a Nuclear Waste Salt Repository Environment* fairly represents my comments, where incorporated, to the peer review panel.

John D. Ditmars

John D. Ditmars

Wyman Harrison

Wyman Harrison

Abraham Lerman

Digby D. Macdonald

Digby D. Macdonald

Robert A. Paddock

Robert A. Paddock

James P. Peerenboom

James P. Peerenboom

Gary S. Was

Gary S. Was

APPENDIX D

CONCURRENCE SHEET

I concur that the Argonne [illegible] Laboratory report on ONWI's [illegible] entitled [illegible] Test Design to Investigate [illegible] [illegible] Salt Repository [illegible] [illegible] in the next revision [illegible].

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

APPENDIX C

ACTION TO BE TAKEN ON THE ARGONNE PEER REVIEW PANEL RECOMMENDATIONS AND PAGE-BY-PAGE COMMENTS

APPENDIX C

ACTION TO BE TAKEN ON THE ARGONNE PEER REVIEW PANEL RECOMMENDATIONS AND PAGE-BY-PAGE COMMENTS

The action statements presented in App. C are in response to Argonne National Laboratory's (ANL's) recommendations and comments in the Summary of Recommendations and Sec. 3, respectively, of this report. The recommendations were abstracted from the detailed discussions in Sec. 2. The action statements reflect ANL's assumption that ONWI and SRPO intend to finalize the reviewed memorandum in essentially its present form after making changes consistent with the action statements. In other words, ANL assumes that ONWI and SRPO do not intend to repeat the test design procedure and issue a completely revised document.

The initial draft of App. C was written by the review session chairman based on the ONWI responses to the ANL peer review report. Those responses had been received by ANL from SRPO on April 21, 1986. (Copies of the responses are in the ONWI and ANL quality assurance files for this peer review.) The initial ANL draft was distributed to SRPO and ONWI on June 4, 1986, for their consideration. It was incomplete in that ANL believed that certain points needed additional response by ONWI. Upon receipt of those additional responses, the initial draft was revised by ANL and distributed to SRPO and ONWI for their final concurrence on September 5, 1986.

ACTION ON ARGONNE RECOMMENDATIONS

Recommendation	Action Statement
1	Several sentences will be added to the end of the first paragraph on page 1 of O/TM-71 to convey the content of the following paragraph. Ideally, the objectives of the test program and the relationship of the test program to the overall waste package program of the SRP should be established in advance by a waste package program plan. Because such a plan was unavailable at the time the panel was directed to develop a test program, the panelists designed a test program based on regulatory requirements, results of completed and ongoing corrosion tests at PNL and Sandia National Laboratories, and their own professional judgment.

Recom-mendation	Action Statement

2 On page 7, lines 25-29 will be modified to include the content of the following discussion.

The model to be developed is expected to be a function of environmental factors (e.g., temperature, magnesium concentration, and oxygen concentration) and other factors (e.g., time and generation of a corrosion products layer). Time will enter into this model explicitly, but also implicitly through the environmental factors that are functions of time. Once models defining the environmental factors as functions of time for a specific scenario are available, corrosion penetration over time can be calculated by integrating numerically or otherwise. Waste package life can then be determined given the corrosion allowance. Further, if the statistical distributions for the varying environmental factors were known, one could define expected waste package life through simulation techniques like Latin hypercube sampling. However, the exact strategy to be adopted by ONWI for determining waste package life is outside the scope of this report. Also, SRPO does not believe that it is important to discuss the strategy for determining container life expectancy in this report because other forms of corrosion and the container's structural response to lithostatic loading would have to be considered. SRPO believes that it is sufficient to state that determination of the general corrosion penetration rate of the container material will be an important part of that strategy.

3 Section 3.3.2.4 will be expanded to include the justifications discussed below.

Data on uniform corrosion of steel in seawater and soil environments were reviewed. Steady state rates are established in these environments after two to five years. Further, PNL has experimental evidence that steady state rates are established after 6-12 months. The panel tried to identify possible scenarios that would result in significant changes in the repository environment after an initial steady state condition had been established. Although none were obvious, the possibility of a significant change occurring during a 1000-year period cannot be ruled out completely. Barring such changes, the panel believed that the initial steady state corrosion rate (i.e., one that would continue in the absence of significant changes in the repository environment with time) would be established after one to two years. The panel believed that, even if a steady state is not achieved within a five-year time frame, the measured uniform corrosion penetration rates would be conservative.

Recom-mendation	Action Statement
4	On page 8, lines 10-13 will be replaced by a paragraph expressing the content of the following sentences. Although the panel exercised all of the above steps, the results of steps 3, 4, and 5 did not play a significant role in the final test design recommended. The difficulty in applying these steps to this test design is discussed throughout this report. The panel decided to emphasize the validity and adequacy of the experimental test design and not the verification of the ONWI-501 methodology.
5	On page 1, lines 20-33 will be modified to define accelerated life testing as discussed in ONWI-501 and to discuss why the panel chose not to consider such testing in the development of the final test design. The reasons given will be based on the following discussion. The panel believed that the uniform corrosion process is not sufficiently well understood to devise suitable accelerated life tests. The rate dependence for any single factor that might be used as an accelerating factor is very uncertain. Thus, the concept of testing at high-stress conditions and then extrapolating to low-stress conditions is inappropriate for the repository environment. Even though the title and abstract of ONWI-501 imply that the document deals only with accelerated life testing, it actually describes a procedure applicable to the design of any multifactor testing program.
6	On page 15, lines 2-4 will be expanded to describe the approach used by the panel to obtain consensus positions, consensus controlling factors and ranges, and consensus predicted corrosion rates. The additional material will include the points made in the following discussion. The techniques used by the panel for arriving at consensus are best described as informal. Experience with a variety of panels has shown that the objective of designing a factorial experiment imposes sufficient structure on the panel so that formal methods are not required. Differences between panel members regarding which variables should be tested and what ranges should be used were generally resolved through open discussion. Differences in the quantitative predictions for each of the test conditions were sometimes resolved by simple recognition of whose arguments were superior and whose data were best. A more formal method was avoided in resolving quantitative differences because experience had shown that scientists are correctly skeptical of the validity of any simplistic mathematical procedure for processing their quantitative estimates.

Recommendation	Action Statement

7 On page 24, lines 14-16 will be replaced by a statement that conveys the content of the following paragraph.

> Ballinger, Cunnane, and Kuhn used the PNL data, whereas Westerman used the Sandia data, to account for the oxygen effect in their predictions. However, during the panel discussions, Westerman pointed out that the oxygen concentration was not monitored during his experiments at PNL and that the oxygen level was therefore unknown for the PNL data.

8 On page 40, lines 13-16 will be modified to include the content of the following paragraph.

> In summary, the need for the ONWI-501 methodology to include measures of uncertainty is recognized by both ONWI and the panel members. Alternative methods for including uncertainty measures in the methodology have been explored; as yet, no particular method has been adopted. Steps are being taken by ONWI to include such measures in future applications of the methodology. Since the consensus predictions did not affect the resulting test design, the lack of treatment of uncertainties in judgment was inconsequential.

The part of the ANL recommendation pertaining to consideration of measurement uncertainties is also addressed by the action statement for the ANL comment for page 37, line 3.

9 A paragraph will be added to the end of Sec. 3.3.1 that will convey the content of the following paragraph.

> In selecting the range of experimental conditions for the controlling factors for the test, the panel considered the anticipated ranges of repository conditions and any changes in these ranges that might occur as the SRP evolves. However, the panel also recognized the potential for diluting the relevant data by considering an unnecessarily broad range for each of the controlling factors. The ranges chosen were based on what the panel considered to be a reasonable compromise between these conflicting concerns.

The justification for the upper bound on the oxygen concentration given in Sec. 3.3.2.3 will be expanded to include the content of the following paragraph.

> The plausible sources of dissolved oxygen that were identified by the panel were atmospheric oxygen and radiolytic oxygen. Although the

Recom-mendation	Action Statement

panel did recognize that trapped air could exceed atmospheric pressure, it concluded that the available porosity was so low that this inventory would be insignificant when considered in light of the stoichiometric equivalent quantity of iron. Preliminary assessment of the radiolytic production rate of oxygen indicated that, for the expected gamma fluxes external to the container, such oxygen would make a relatively insignificant contribution to the total corrosion reaction rate. Hence, the panel concluded that the saturation concentration at one atmosphere of air represented a reasonable upper bound.

Section 3.3.2.2 will be modified to indicate that the magnesium concentration range proposed by the panel was based on the plausible range for the candidate site in Deaf Smith County, Texas.

10 The word "greatly" will be removed from line 3 on page 43.

On page 43, lines 6-11 will be changed to: "In order to test a spectrum of material heats, it is recommended that five heats of steel conforming to A216 Grade WCA specifications be obtained from different steel foundries and carefully characterized. These materials, along with weldments of each material (prototypic, if possible), should be corrosion tested, in the as-cast condition only, in certain key corrosion tests described in the following example of a proposed test matrix."

On page 43, lines 17-20 will be replaced by several sentences conveying the content of the following paragraph.

> It is the premise of the panel that the general corrosion rate will not be very sensitive to the range in values of metallurgical variables that might occur from heat to heat of the material and that could therefore be accounted for by selecting a conservative corrosion rate for use in the development of predictive models. However, should marked differences appear in corrosion behavior, the compositional-microstructural factors responsible must be determined so that those factors can be controlled during the founding of the material to be used in waste-package fabrication. Such an effort would involve designing additional tests using specimens prepared under carefully controlled conditions to establish the relationship between the metallurgical variables and corrosion rate.

11 The discussion of the reasons why radiation was not considered by the panel to be a major controlling factor (page 17, lines 34-39) will be modified to include (1) specific reference to the PNL empirical observations that dose

Recom-mendation	Action Statement
	rates less than 3000 rads per hour had little effect on the uniform corrosion rate and (2) a statement that the panel believed (giving reasons, if possible) that the production rate of radiolytic oxidizing species for the expected radiation flux would be insufficient to support a significant contribution to the uniform corrosion rate.
	The statement on lines 29-30 of page 17 concerning the elimination of pressure from consideration will be changed to indicate that the panel believed that the potentially important pressure factor is not the total pressure but the partial pressure of hydrogen, which is addressed in the supplementary tests of Sec. 4.2.
	Section 3.3.2.2 or some other appropriate paragraph or section will be modified to state that, even though the panel selected the magnesium concentration to characterize brine composition in the proposed tests, PBB1 and PBB3 brines are to be used as the nominal or base composition of the test brines so that the details of brine composition are not completely ignored. The revision will also state that the panel did not consider other brine composition variables as key controlling factors because there is no reason to believe that the uniform corrosion rate will be sensitive to variations in these other factors and that there is no reason to expect that these factors will change with time. SRPO's plans to fully characterize expected brine chemistry and to conduct tests to determine the sensitivity of corrosion behavior to all of the potentially significant brine components will also be mentioned.
	On page 17, lines 28-33 will be modified to state that the panel expects that site selection criteria will exclude sites having significant brine flow-through rates. The revised paragraph will also state that the panel therefore only considered tests with extremely slow flow/refreshment rates, that is, those in which the flow/refreshment rate itself would not be considered a significant variable.
12	Section 3.9 will be modified according to the action statements in response to the ANL page-by-page comments concerned with that section. The type of test vessels and the test coupon sizes will be briefly discussed.
13	Material conveying the content of the following paragraph will be added to page 38, lines 13-16.
	After concluding that the full factorial test matrix was too large for practical implementation, the panel decided to implement a partial matrix and evaluate the resulting data using a technique such as that described in App. D, together with the hierarchical tree analysis, to

Recom-mendation	Action Statement

see if modifications to the overall test matrix were warranted. This approach provides the flexibility needed to change the test design as more and more data become available. In other words, the results from the partial-matrix tests and the supplementary tests described in Sec. 4.0 are expected to guide the redesign of the test matrix, which is seen as both dynamic and evolutionary.

Section 3.11.2 will be expanded to include the content of the following paragraph.

The panel's decision to begin most of the five-year tests as soon as possible was based on the limited time left before the license application process must begin. Three levels of magnesium concentration would, in the opinion of the panel, provide reasonably adequate data to describe any quadratic dependence of the magnesium effect within the selected range. Preliminary analysis of the consensus-predicted corrosion rates as shown in App. D bears out this expectation. Selection of the three proposed magnesium concentration levels and two of the five temperatures for the initial short-term tests was based on the technical judgment of the panel that these test conditions would offer the best possibility for producing meaningful data for development of predictive models and for selection of the follow-on tests.

14 The importance of the supplementary tests is addressed in the action statements related to other ANL recommendations and comments, such as that in response to recommendation 13.

The following sentence will be added after line 28 on page 41: "Specific strategies for implementing the supplementary tests will be developed and documented in a detailed test plan."

15 The first part of the action statement in response to ANL recommendation 13 and that in response to recommendation 17 address this recommendation.

16 Sentences presenting the following points will be added after lines 29-38 on page 21.

All panel members had access to the results of the PNL corrosion studies. Panel members were encouraged to consider those results, but also to develop their own sources and make their own predictions. The hope was that any new data and approaches discovered would increase the panel's overall knowledge. The predictions are essentially guesses based on limited data and on individual professional judgment.

Recommendation	Action Statement
17	On page 28, the material in lines 38-42 will be expanded to convey the content of the following paragraph. The panel concluded that the data base used for predicting the corrosion rates was unreliable, and it refused to rely on the consensus tree to either prune or add intermediate levels to the test matrix. The panel believed that these predictions were inconsistent and that the uncertainties in them were so large that the predictions had limited value in guiding the experimental design. The panel was therefore compelled to resort to designing the tests in an ad hoc fashion. The only conclusion that the panel could draw from these predictions was that the physical and chemical principles governing corrosion rates are not well understood. However, the panel left open the possibility of revisiting the issue of pruning the test matrix once intermediate levels are added to the matrix. The panel also believes that, when more experimental data become available, analysis of those data using hierarchical trees or similar analyses will yield a better understanding of the physical and chemical principles governing corrosion and may result in the need to modify the proposed test matrix.
18	On page 33, lines 11-15 will be modified to state that the supplementary tests involving solid salt and PBB3 brine proposed in Sec. 4.1 are meant to provide data on the effect of amakinite. On page 44, lines 1-12 will be changed to point out that the corrosion research program recommended by the panel should be considered basic research; although important to the understanding of corrosion, the detailed planning of such research is beyond the scope and intent of O/TM-71.
19 and 20	The introductory material in App. D will be expanded to convey the content of the following paragraphs. The objective of the method presented in this appendix is to evaluate the adequacy of the data generated by implementing a partial factorial test matrix compared with that of data supplied by implementing the full factorial matrix. If the data already generated by the partial matrix meet the adequacy criteria, further testing would be unnecessary. In effect, the original full factorial matrix would be pruned to the partial matrix already implemented. Adequacy will be determined in terms of the fraction of the variance explained by the data from the partial matrix, assuming that the data from the full matrix of tests would meet the requirements. Then, the criteria will

Recommendation	Action Statement
	be a predetermined percentage (i.e., 95, 99, 99.99, etc.) that will depend on the results of a cost-effectiveness analysis involving the cost of running the remaining tests against the additional information that would result from those tests. As indicated in this appendix, the data corresponding to the full matrix of tests would be those from the partial matrix of tests supplemented by predicted corrosion rates for the rest of the test conditions. These predictions would be based on the newly available data base and models.
	The method presented is an ad hoc technique, which is simply used to indicate one possible method for making such evaluations. It would be necessary to develop the technique more thoroughly for general application.

ACTION STATEMENTS FOR PAGE-BY-PAGE COMMENTS

Page	Line(s)	Action Statement
xi	6-13	The figure titles will be changed to reflect the differences.
1	3-6	The term "uniform corrosion" will be used. "Under general corrosion conditions" will be replaced by "for uniform corrosion failure mode."
1	9	The comma will be deleted.
1	23	The sentence will be changed to: "Consequently, an experimental design that defines the tests should consider both the necessary scientific objectives and the inevitable constraints of economy and time."
1	29	The paragraph will be changed to include a definition of accelerated testing as used in ONWI-501.
1	39	"Multifactor life test" will be changed to "series of multifactor tests."
2	17-24	The text will be modified to be consistent with the figure.
5	22	The text will be changed to read "technical evidence as interpreted."
5	29-31	The sentence will be changed to: "The test program designed in this effort will provide a data base that is expected to be needed to estimate container life, assuming uniform corrosion in a repository-relevant brine environment."

Page	Line(s)	Action Statement
6	11-13	The following reference will be added for the "early corrosion studies": Westerman, R.E., and S.G. Pitman, 1984, *Corrosion of Candidate Iron-Based Waste Package Structural Barrier Materials in Moist-Salt Environments*, in Scientific Basis for Nuclear Waste Management VIII, Materials Research Society Symposia Proceedings, *44*:279-285.
6	13-14	The text will be modified to characterize the brines.
6	21-24	The sentence will be expanded to read: ". . . are not inevitable, in the case of nonhardened mild steel, as indicated by its satisfactory behavior in long-lived structures such as buildings and bridges."
6	26-27	The reference to "Westerman et al., 1985" will be corrected here and elsewhere in O/TM-71.
6	32-33	A reference to BMI/OMWI-517 will be added.
6	36-39	The phrase "by the panel" will be inserted after "judged."
7	4	The report will be reviewed for instances of confusing terminology as described in the ANL comment and modified for consistency in describing the controlling factors.
7	7-8	The following sentence will be inserted after the sentence on lines 9-11 of page 7: "This matrix will form the basis for careful analysis and pruning and may result in a partial matrix being recommended for testing."
7	16-17	A sentence or two will be added that indicate that the condition of unlimited brine is a hypothetical scenario that does not represent the expected conditions in the repository. The scenario is assumed to define an environment that will ensure that sufficient brine is always in contact with the waste package so that corrosion is not limited by the availability of brine.
7	21	The comma will be removed.
7	25	The report will be modified to indicate that time will enter the model in two ways -- both explicitly and through the environmental factors that are functions of time.
7	25-27	The report will be modified to acknowledge the potential difficulty in integrating corrosion rates over time under changing environmental conditions when the corrosion rate may depend on the previous history of the container material (e.g., earlier development of a corrosion-products layer).

Page	Line(s)	Action Statement
7	30-41	The applicability of the ONWI-501 methodology to multifactor testing in general, not only accelerated life-cycle testing, will be noted in the report.
7	39	The words "numerical estimates" will be replaced with "numerical estimates of corrosion rates."
7	41	The words "hierarchical trees" will be replaced with "hierarchical trees to graphically display the anticipated interactions among the factors and corrosion rates."
8	8-9	The text will be modified to include definitions of the terms "main effects" and "interactions" as used in ONWI-501 and O/TM-71.
8	10-11	The sentence will be changed to: "The emphasis of the panel was on evaluating the validity and adequacy of the experimental design through the consensus judgment of the panel members and not to verify the ONWI-501 methodology."
8	20-27	The following sentences will be added after line 27: "No specific attempt was made to identify the potential biases of individual panel members nor to mitigate the effect of possible biases on the test design. Individual bias is expected to be eliminated from the proposed test design because the design is based on the consensus judgment of the expert panel as a whole."
11	5-7	The sentence will be replaced by: "The overall objective of the expert panel approach, as recommended in the ONWI-501 methodology, is to assure that the test design will satisfy the data-generation requirements of scientists who are knowledgeable in the subject area and will therefore address the needs of the waste package design and performance assessment aspects of the SRP."
11	17-18	This comment is addressed by the action statements in response to the ANL comments for page 7, lines 30-41, and page 11, lines 5-7.
12	2-6	The action statement in response to ANL recommendation 7 addresses this comment.
12	9-12	In line 10, the words "or add" will be added after "eliminate"; in line 11, "this elimination" will be changed to "the elimination."
12	16-18	This comment is addressed by the action statement in response to the ANL comment for page 7, lines 30-41.

Page	Line(s)	Action Statement
12	37-39	The content of the following paragraph will be added at the end of Sec. 2.2.2. To determine the number of samples per test on a statistical basis, one needs a model and performance criteria for the measured corrosion rates. These needs have not yet been defined. Also, the number of replicate specimens per test condition must strike a balance between experimental resources available and statistical needs. Thus, the supplementary tests would generally involve duplicate specimens, whereas the main tests would involve a larger number (namely five), consistent with a reasonable estimate of resources available and the need to optimize the statistical results for those perceived resources. Statistically, five samples should provide sound estimates of mean corrosion rates. Again, the number chosen is arbitrary.
13	2-16	The action statement in response to ANL recommendation 2 addresses this comment. The text in Sec. 2.2.3 will be modified to include a summary of that statement.
13	8-10	The text will be modified according to the ANL comment.
13	15	The word "integration" will be replaced by "prediction."
13	37-40	The last part of the sentence will be changed to ". . .and how critical the topic is to the overall program."
13	35-37	The sentence will be changed to: "On the basis of its experience with the present test-design problem, the panel concluded that developing a test design with detailed documentation could be accomplished in five meetings of one, two, one, two, and two days' duration."
15	8-10	A statement will be added to the end of the first paragraph in Sec. 3.1 to the effect that the techniques used by the panel for arriving at consensus are best described as informal.
15	11-21	The text will be modified to state that accelerated life testing is not applicable to material testing because of the lack of a clear and absolute definition of material failure and that accelerated tests were not considered by the panel because of suspected changes in the corrosion mechanism at high temperatures and high magnesium concentrations.

Page	Line(s)	Action Statement
15	18-19	The sentence will be changed to: ". . .and (2) to recommend a factorial matrix of tests that bounds the 'dominant' factor space and a set of supplementary tests designed to cover unanticipated scenarios and confirm or verify the panel's judgment in identifying the dominant factor space."
15	22-35	Because the only justification for these assumptions is the judgment of the panel, no change in the text is needed.
15	25	"Geothermal environments" will be changed to "underground environments," and the National Bureau of Standards Circular No. 579 will be referenced.
15	32-35	The sentences will be replaced by several sentences that convey the content of the following paragraph. This power factor was derived using basically the same seawater data but at a time when very few additional repository-relevant corrosion data were available. In the opinion of the panel, a power factor of unity would be a more conservative bound when extrapolating the results of a relatively short experimental program to the long times (several hundreds of years) required for application in a repository environment.
15	36	The words "to the estimated test results developed by the panel" will be inserted after "predictive model fitting."
15	40	The word "data" will be replaced with "estimated test results developed by the panel."
15	40-43	The phrase "of the feasibility" will be added after "in terms."
15	43-45	The sentence will be changed to: "These polynomial models may fit well within the bounds of the factor space of the test conditions, but the predictive capability of these models is limited and uncertain when extrapolated outside this space or when interpolated within this space between widely separated test conditions."
16	12-13	A paragraph will be inserted after the second paragraph on page 16 to convey the content of the following material. The panel also recognizes the potential importance of brine chemistry variables other than magnesium concentration. The panel recommends that the SRP undertake full characterization of the brine chemistry and tests to determine the sensitivity of the corrosion behavior to all the potentially significant brine components.

Page	Line(s)	Action Statement
16	19-26	The paragraph will be expanded to indicate that inclusion brines could contain additional oxygen from trapped residual atmospheric oxygen or radiolytic oxygen, but that the panel judged such sources to be relatively unimportant because the stoichiometric equivalent amounts of iron would be quite small.
16	27-36	A sentence will be added near the end of the paragraph, stating that the availability of brine in infinite quantities (i.e., unlimited brine) does not imply that high brine flow or refreshment rates are to be used in the tests.
17	10	No action is required.
17	25	The word "primary" will be changed to "fundamental."
17	26	The sentence will be changed to: "Variables other than the controllable fundamental variables were eliminated because, within the expected range of repository or test conditions, they were expected to have an insignificant effect on the corrosion rate."
17	28-30	The first sentence will be changed to: "Metal aging effects were deemed to be insignificant for anticipated container temperatures because mild steels have historically been used at such temperatures without signs of serious aging phenomena." The following sentence will be added after the second sentence: "Except for the supplementary tests for hydrogen pressure effects, the pressure will not be controlled; that is, it will simply be at the level generated by the gases."
17	30-32	The paragraph will be expanded to include the points made in the following material. The conditions that will actually exist in a repository at the surface of a waste package are unknown. Certain assumptions, which may be highly arbitrary but which are hoped to be generally conservative, must be made in order to define attainable test conditions. In the present case, an all-liquid system was chosen to allow replenishment of depletable species in a low-reactant-concentration environment. Such systems are relatively difficult to manage experimentally if a solid phase is incorporated into the liquid phase. This choice appears to be conservative based on the results of recent experiments at PNL (unpublished data). Flow was not considered because scenarios involving significant brine flow velocities in the vicinity of the waste package container in a repository in salt were not considered credible.

Page	Line(s)	Action Statement
17	32-33	The term "primary measured variable" will be changed to "measured response variable."
17	34-39	The action statement in response to ANL recommendation 11 addresses this comment.
18	21	"Oxygen fugacity" will be changed to "oxygen concentration."
18	31	The word " 'stress' " will be changed to "the effect on corrosion rate."
19	9-12	Sandia National Laboratories report SAND-1585 will be referenced.
19	13-20	A reference to support the magnesium concentration limits discussed will be added.
21	1-6	The action statements in response to other ANL recommendations and comments (e.g., recommendation 9 and the comment for page 16, lines 19-26) address this comment.
21	7-27	A short introductory paragraph will be added to the beginning of Sec. 3.3.2.4 to convey the content of the following material. The panel did not have sufficient information to estimate the exact form of the expected corrosion rate as a function of time. However, the panel assumed that the general form of the functional relationship begins with a high corrosion rate that gradually decreases, reaching a steady state in about one to two years.
21	17-19	A reference to the PNL FY 1984 Annual Report (Westerman et al., 1986) will be added.
21	20-22	The action statements in response to other ANL recommendations and comments (e.g., recommendation 3) address this comment.
21	39-42	The action statement in response to ANL recommendation 16 addresses this comment.
23	3	A few sentences conveying the content of the following paragraph will be added to the end of the paragraph that concludes with line 3 on page 23. In the absence of sufficient information on the corrosion process under repository conditions, the panelists used the very limited data available, along with their intuition and expert judgment, to

Page	Line(s)	Action Statement
		predict the expected corrosion rates. As judged by the panel, the available data were not from tests in which all the dominant factors were controlled or monitored. Consequently, the predicted corrosion rates were as varied as the individual intuitions and judgments of the panelists. However, the panel did agree on the list of identified dominant factors and their operating ranges in the repository.
23	15-25	A reference to ONWI-501 will be added.
24	1-4	The action statement in response to ANL recommendation 17 addresses this comment.
24	15	"They" will be changed to "the panel."
24	19	The unit "mm" will be changed to "mm/yr."
24	29-30	The word "arithmetically" will be inserted before the word "averaged."
24	32-33	The value "1.125 mm" will be changed to "1.145 mm/yr."
24	35	"1.92" will be changed to "1.955 mm/yr."
25		The first paragraph in Sec. 3.6 will be expanded to include the following points. Because of the method used to calculate the consensus corrosion rates and because some panelists withdrew some of their predicted corrosion rates, the resulting consensus corrosion rates of Table 3-2 do not always reflect the trends of the predictions of individual panelists. For example, lines 5 and 7 of Table 3-2 show that even though the individual panelists estimated that the higher magnesium concentration would result in the same or higher corrosion rate compared with the lower magnesium concentration, the consensus corrosion rates exhibit the opposite trend. It is because of this kind of conflict between the anticipated trends and the consensus predictions that the panel eventually decided not to rely heavily on these consensus corrosion rates when designing the test matrix.
27		The numbers referred to in the comment will be corrected in Figs. 3-3 and 3-5.
28	38-42	The action statement in response to ANL recommendation 17 addresses this comment.

Page	Line(s)	Action Statement
31	11	The paragraph will be expanded to include the content of the following paragraph. The premise for not selecting additional oxygen levels was that the brine would be highly anoxic under expected conditions or that the brine could have significant dissolved oxygen if it resulted from an intrusion scenario. The panel assumed that, if dissolved oxygen or other oxidizing species were to contribute significantly to the cathodic reaction, the rate would likely be limited by the availability of such species.
31	16-19	The sentence will be changed to: "On the basis of a review of the literature related to the existing low-carbon steel data base for repository relevant conditions, ..."
32	15-17	Reference will be made to E. Smailos, W. Schwartzkopf, and R. Foster, personal communication (1985).
32	21-30	The phrase "in environments that excluded free oxygen" will be added to the end of the first sentence of the paragraph.
33	11-14	The following sentence will be added at the end of the paragraph: "In any case, it is the panel's opinion that, although the effects of other brine constituents on corrosion are not presently known, their effects will not be significant compared with the effect of the magnesium concentration."
33	25	The text will be modified to indicate that the reason for selecting a geometric sequence is the suspected logarithmic relationship between corrosion rate and time.
34	21-23	The phrase "based on the experience of the panelists" will be added to the end of the sentence.
34	25-28	A sentence or two will be added to Sec. 3.9.1.2 to convey the content of the following paragraph. Metal dissolution and the liberation of corrosion products may cause variation in the composition of the brine in a repository setting. Generally speaking, however, accumulation of corrosion products is expected to impede the corrosion reaction; therefore, such effects are not considered by the panel to be of primary importance to these tests.

Page	Line(s)	Action Statement
34	28-31	The sentence will be changed to: "While there is no way to guarantee a perfectly uniform brine composition throughout the test vessel, the effect of nonuniformities on the resulting corrosion rate can be minimized by using flowing . . . ."
35	2-15	The text will be modified to indicate that 50 ppb is the approximate order of the minimum oxygen concentration level achievable in an experiment.
35	7-13	The sentence beginning "The former method . . ." will be deleted.
35	23-24	The text will be modified to indicate the following: The frequency of oxygen sampling will depend on the oxygen concentration and the reactivity of the specimen assembly. For example, anoxic tests should probably be sampled at least weekly, while tests with high oxygen concentrations at high temperatures should most likely be sampled daily.
35	24	The text will be modified to clarify the point that the term "approximately monthly" was simply meant to provide an order of magnitude for the sampling frequency and was not meant to supersede the timed examinations presented in the test matrices (i.e., three months, six months, one year, etc.).
35	38-39	The phrase "based on the experience of the panel" will be added to the end of the sentence. The rest of this comment is addressed by the action statements in response to ANL recommendation 12 and other ANL recommendations and comments.
36	7-13	Section 3.9.2.3 will be expanded to describe more completely how hydrogen gas can be handled experimentally. The revised section will convey the content of the following paragraph. Determining the corrosion rate by measuring the hydrogen pressure is only possible when oxygen is provided by the water and the products of the reactions are well known. Hydrogen gas is not expected to diffuse through the pressure vessels under the relatively low temperature test conditions noted. The test vessels must be leak tight (e.g., seal welded) to permit the use of this method. Typically, the autoclave back-pressure valve would be set at a level approximating that expected under postclosure conditions in an actual salt repository (i.e., 14-17.5 MPa). Hydrogen generated in excess of this back pressure would be vented (unmeasured) from the system. This test condition would

Page	Line(s)	Action Statement
		approximate a repository condition in which the hydrogen pressure would be allowed to build up to a certain value, but would not be allowed to exceed lithostatic pressure. There are other ways to handle hydrogen. For example, it could be allowed to bleed from the system at a pressure less than lithostatic, which is analogous to its diffusion into the salt horizon under the influence of an activity gradient. At the present time, however, it is not known what hydrogen pressure could be retained in the repository under postclosure conditions, as the permeability of salt to hydrogen is not well understood.
36	15-22	The paragraph will be modified to include the points in the following paragraph. The hydrogen ion activity is difficult to measure in brines, especially at elevated temperatures. However, the hydrogen ion concentration in a test system must be estimable with some confidence, as it very strongly influences the corrosion mechanism manifested by a mild steel specimen in a given test environment. Approaches for making such measurements are under investigation as part of the SRP. Until suitable approaches are available, the pH of a test will not be determined under actual test conditions, except where periodic environmental sampling can be performed without difficulty (e.g., flowing autoclave tests). However, before and after all tests, the hydrogen ion concentration will be determined at ambient temperatures using a titration technique.
37	3	The first paragraph on page 37 will be modified to convey the content of the following paragraph. At the time of the panel meetings, a corrosion model or an accuracy criterion for corrosion rates had not been defined. Consequently, the number of replicates was chosen on an ad hoc basis to strike a balance between the experimental resources available and statistical needs. Five replicates should provide a good estimate for the mean corrosion rate and a reasonable estimate for its variability.
37	7-8	The end of the sentence will be changed to ". . .the initial test design requires 250 specimens for each of the five time levels, for a total of 1250 specimens."
37	10-11	The phrase "the procedures to run these tests were" will be replaced by "a brief general description of these tests was."

Page	Line(s)	Action Statement
38	18-37	The action statement in response to ANL recommendation 13 addresses this comment.
39	7-9	The action statements in response to ANL recommendations 19 and 20 address this comment.
39	10-14	The text will be modified to indicate that there are two anticipated uses for these predicted corrosion rates. The first is in applying an approach such as that described in App. D to evaluate the available data; the second is to check the data from longer-term tests.
39	16	The word "correctly" will be deleted.
39	16-33	The action statement in response to ANL recommendation 5 addresses this comment.
41	10	The text will be modified to indicate that the supplementary tests will use two specimens each and that this number was chosen because these tests are designed to screen for potential effects on corrosion rates and not to precisely quantify those rates.
41	28	The text will be modified to convey the content of the following paragraph. PBB3 brine represents inclusion brines and PBB1 represents intrusion brines anticipated under repository conditions. PBB1 has a magnesium concentration very similar to the lowest level of magnesium in the main test matrix, which also has an intermediate level very similar to the magnesium concentration in PBB3.
42	1-17	Lines 12-17 will be deleted, and the following sentence will be added at the end of line 11: "Most of these tests have already been completed, and the panel found no reason to repeat these tests at another temperature." The specified oxygen level for all the supplementary tests will be changed to "zero," or the equivalence of a level of 50 ppb with the lowest oxygen level readily attainable experimentally will be mentioned.
42	9-11	An introductory statement will be added before the second set of tests involving all-liquid tests at 200°C. The fact that these tests may be eliminated will be discussed.

Page	Line(s)	Action Statement
42	19-34	The action statement in response to the ANL comment for page 36, lines 7-13, addresses how hydrogen gas can be handled experimentally.
42	22	Numerical pressure values will be expressed in metric units throughout the report.
42	28-31	The phrase "welded static reaction vessel" will be changed to "seal-welded static reaction vessel."
42	36-41	The specified oxygen levels for the tests in Secs. 4.2 and 4.3 will be changed to "zero." Section 4.2 will be modified to state that the temperature levels were chosen because they are reasonable for expected repository conditions and because they are far enough apart to enable thermodynamic principles to be applied to the resulting data. Section 4.3 will be modified to state that the temperature levels were chosen because they are reasonable for expected repository conditions and because they are far enough apart to provide an opportunity for ascertaining any changes in the corrosion mechanism.
42	40	The label should be "ppb"; however, the oxygen level will be changed to "zero" for all the supplementary tests to be consistent with the levels specified for the main text matrix.
43	26-32	The magnesium concentration for these tests will be changed to the magnesium solubility limit for the test conditions. The introductory paragraph in Sec. 4.4 will be modified to reflect this magnesium concentration and to indicate that this concentration is being investigated because the upper limit on magnesium concentration expected in inclusion brines is not yet well established.
44	1-12	The action statement in response to ANL recommendation 18 addresses this comment.
45	3-10	The following sentence will be inserted in the first paragraph of Sec. 5.0: "However, the Sandia data were used by some of the panelists in developing their predictions of corrosion rates, as discussed in Sec. 3.4."
46	8	The ANL comment needs no specific action.

Page	Line(s)	Action Statement
47	10-13	The second sentence of the second paragraph on page 47 will be changed to: "On the basis of their knowledge of the existing corrosion test program, the panelists expect that such a large test matrix would demand a significant increase in facilities and personnel over current levels."
47	22-27	The action statements in response to other ANL recommendations and comments, such as those for recommendations 13 and 17 and the comment for page 39, lines 10-14, address this comment.
47	28-29	The sentence will be changed to: "An expert team approach, using the administrative procedures described in the ONWI-501 report, was used to develop the above test matrices."
48	3-5	The action statement in response to ANL recommendation 1 addresses this comment.
50	1-4	The list of references in Sec. 7.0 will be reviewed and corrected. Generally, only published documents will be referenced. If necessary, reference citations will specifically identify documents that are unpublished or not readily available.
69	20-26	Units for the coefficients and constants in the equations referred to in the ANL comment will be added to the text.
81	13-14	Sentences that convey the following points will be added after the first sentence of the second paragraph on page 81. Data for all seven alloys were used because data for A216 steel, per se, are relatively limited and because low-alloy steels are expected to corrode at similar rates in the same environment. The panel thought that using data for all the steels available would lead to a more accurate assessment of data trends as far as variations in environmental stress parameters than would the use of A216 data alone. The beginning of the second sentence of the second paragraph on page 81 will be changed to: "Corrosion-rate estimates were made for 'oxic' conditions and . . . ."
81	21-28	The units on the activation energies will be changed to "cal/mole."
86	11-12	The sentence beginning "My factor of 1/2 . . ." will be changed to: "My factor of 1/2, which obviously has no fundamental significance in terms of mathematical models of corrosion kinetics, provides an admittedly arbitrary rate lying between the two extremes observed."

Page	Line(s)	Action Statement
87	11-15	No action is required because the particular extrapolation/ interpolation equation was chosen by an individual panelist as he made his predictions.
87	19-21	Further justification for the choice of a factor-of-10 reduction in corrosion rate data will be added.
91	18	The phrase "fitting standard orthogonal polynomials" will be changed to "fitting a set of standard orthonormal polynomials."
91	19	The word "estimate" will be changed to "compute."
91	20	The phrase "terms in the" will be deleted, and the word "terms" in line 21 will be changed to "polynomials."
91	20-22	The book *Factorial Designs* by Raktoe et al. will be referenced.
91	37-38	The phrase "are associated with the interactions and" will be inserted in line 30 on page 91 after the phrase "remaining 40 projections." The sentence on lines 37-38 will be replaced by several sentences conveying the content of the following paragraph. The magnitude of each of the 50 projections represents the hierarchy of importance of retaining the associated polynomial in the expansion. The importance of a particular polynomial can generally be interpreted as indicating the importance of the highest order term in that polynomial. The phrase "terms of the fitted polynomial" on line 39 will be replaced by the word "polynomials," and the word "terms" on lines 40 and 41 will be changed to "polynomials."
92	4-7	The phrase "can be neglected" will be changed to "are sufficiently well estimated and are negligibly small."
92	12-19	The paragraph on lines 9-11 of page 92 will be expanded to convey the content of the following paragraph. The interpolation scheme depends on the expected behavior of the response function with respect to the controlled variables. In this example, because of the suspected logarithmic relationship between corrosion rate and the controlled variables, geometric means are used in the interpolation scheme.

Page	Line(s)	Action Statement
		The phrase "(geometric means)" will be inserted after "interpolated values" on line 12 of page 92.
92	24-25	The phrase "least square estimates of the magnitudes" will be changed to "computed magnitudes."
92	27-32	The text will be modified so that the cubic effect of temperature (1.37 mm/yr) is included in the list of the eight largest effects.
92	33-34	A sentence that conveys the following point will be added at the end of line 32. To ensure that these important main effects and interactions are determined, a minimum of two levels of oxygen, three levels of magnesium, and four levels of temperature (i.e., a 2 x 3 x 4 factorial design) is required.
92	35	The phrase "fitted polynomial coefficients" will be replaced by "fitted polynomial coefficients from Table D-2."
92	39-41	The text will be modified to indicate that the resulting fit (corresponding to Table D-3) to the subset (24 members) of the original complete set of 50 orthonormal polynomials represents a least-squares fit to the original 50 "data" points in the traditional sense. The text will be expanded to include the points made in the second paragraph of the ANL comment.
93		Table D-1 will be corrected as indicated in the ANL comment.
95		Table D-2 will be corrected as indicated in the ANL comment.
96		Table D-3 will be corrected as indicated in the first two ANL comments concerning the table. However, no change in the totals of Table D-3 is required, except to maintain consistency when other changes are made. The notation for the interactions in lines 11, 12, 23, and 24 of Table D-3 will be changed to be consistent with the notation used elsewhere in the table.
97	3-4	The interpolation scheme described here will be modified to correspond to the interpolation scheme described on page 92 and in Fig. D-1. The notation used in the formulas that explain the interpolation scheme will be clarified.

CONCURRENCE

I concur with the action statements, as presented in App. C, which are in response to the recommendations and comments of Argonne's review report entitled *Radioactive Waste Isolation in Salt: Peer Review of the Office of Nuclear Waste Isolations's Draft Report on Multifactor Test Design to Investigate Uniform Corrosion of Low-Carbon Steel.*

J.A. Carr 11/7/86 / Siva Gopal 11/11/86.

J.A. Carr, Office of Nuclear Waste Isolation

W. Harrison

W. Harrison, Argonne National Laboratory

Kang Kun Wu 11/14/86

K.K. Wu, Salt Repository Project Office

APPENDIX D

CREDENTIALS OF PEER REVIEW PANEL MEMBERS

John D. Ditmars

Princeton University: B.S.E., Civil Engineering (1965)
California Institute of Technology: M.S., Civil Engineering (1966)
California Institute of Technology: Ph.D., Civil Engineering (1971)

Dr. Ditmars is Senior Engineer and leader of the Hydrologic and Geologic Engineering Section of the Geoscience and Engineering Group of the Energy and Environmental Systems Division at Argonne National Laboratory. Measuring and modeling portions of the hydrosphere affected by energy technologies and natural resource development has been the main research area of this section. Particular attention has been given to evaluations of model performance and to experimental designs for the acquisition of data at prototype scales for performance evaluation. Dr. Ditmars has extensive experience in measuring and modeling transport and mixing processes in the hydrologic environment. He was for several years responsible for the annual literature review in the area of "Mixing and Transport" for the *Journal of the Water Pollution Control Federation* and is Vice Chairman of the Executive Committee of the Hydraulics Division of the American Society of Civil Engineers. He is also Chairman of the Task Committee on Verification of Models of Hydrologic Transport and Dispersion for the Hydraulics Division of the same society and, as such, has been concerned with the generic aspects of verification and validation as well as with those aspects of particular models.

Before joining Argonne in 1977, Dr. Ditmars was Assistant Professor of Civil Engineering at the University of Delaware. From 1970 to 1972 he was Visiting Assistant Professor in the Water Resources and Hydrodynamics Division of the Civil Engineering Department at the Massachusetts Institute of Technology. His teaching and research activities at those institutions focused on hydraulic engineering and fluid mechanical processes in the natural hydrologic environment and involved analytical and numerical modeling as well as laboratory and field experiments. He is author of more than 45 technical publications in these areas.

Wyman Harrison

University of Chicago: S.B., Geology (1953), after three years of undergraduate work at Stanford University
University of Chicago: S.M., Geology (1954)
University of Chicago: Ph.D., Geology (1956)
Registered Geologist, No. 2476, State of California
Certified Professional Geologist, No. 134, American Institute of Professional Geologists, and No. 487, State of Virginia

Dr. Harrison is Associate Director for Geoscience and Engineering for Argonne National Laboratory's Energy and Environmental Systems Division. He directs a 25-person group that performs analytical and experimental studies related to management of energy and mineral resources and to development and deployment of related technologies. Major activities of the group include (1) acquisition of geophysical and geotechnical data bases, (2) analysis of the data of geoscience to support design and deployment of energy technologies, and (3) development of physical and mathematical models of geophysical and geotechnical systems.

Dr. Harrison's group recently completed comprehensive surveys of geoscience data pertaining to crystalline rock complexes in the northeastern and Lake Superior regions of the United States to help assess their potential as possible sites for repositories for high-level radioactive waste. He and his group were the first to apply formal decision analysis for determining the relative favorability of specific crystalline rock areas for such repositories. Dr. Harrison has conducted numerous other geotechnical projects at Argonne, ranging from field studies of the feasibility of using dredged material to reclaim abandoned mined lands to projecting future Soviet oil output by assessing the development of its giant fields.

From 1971 to 1975, Dr. Harrison was Professor of Geography (Associate Department Chairman) at the University of Toronto, where he specialized in studies of slope stability in sedimentary terrains and the siting of supertanker ports. Before that, he was Associate Director for Physical, Chemical, and Geological Oceanography at the Virginia Institute of Marine Science and a Professor of Marine Science at the College of William and Mary. Dr. Harrison was Director of Environmental/Science Services Administration's (now National Oceanic and Atmospheric Administration's) Land and Sea Interaction Laboratory from 1964 to 1968. Earlier he was on the faculty of Dartmouth College's Department of Geology and geologist with the Indiana Geological Survey.

An author of more than 125 papers, reports, reviews, and books, Dr. Harrison was made Senior Scientist at Argonne in 1976.

Abraham Lerman

Hebrew University, Jerusalem, Israel: M.Sc., Geology (1960)
Harvard University: Ph.D., Geology (1964)

Dr. Lerman joined the Department of Geological Sciences at Northwestern University in 1971 as Associate Professor and has been Professor since 1975. Dr. Lerman has extensive experience in aqueous geochemistry, geochemistry of brines, isotope geochemistry, and radionuclide migration. He is a resource consultant on waste packaging and geochemistry for the Basalt Waste Isolation Project Overview Committee. During 1980 Dr. Lerman was a member of the Backfill Evaluation Panel for Battelle's Pacific Northwest Laboratory.

While associated with Northwestern University, Dr. Lerman has served, at various times, as a visiting professor at several European universities. Before joining the faculty at Northwestern, he was a Research Scientist in Chemical Limnology at the Canada Centre for Inland Waters (1969-1971), a Visiting Investigator and Senior Scientist in Isotope Research at the Weizman Institute of Science (1966-1969), an Assistant Professor of Geology at the University of Illinois at Chicago Circle Campus (1965-1968), a Visiting Investigator (geochemistry) at Lamont-Doherty Geological Observatory of Columbia University (Summer 1965), and a Lecturer and Assistant Professor of Geology at Johns Hopkins University (1964-1965).

Dr. Lerman has published extensively in the areas of geochemical processes in water and sediments, halite and brines, chemical limnology, geochemical cycles, and radionuclides in sediments. He is a member of five professional societies and a Fellow of the Geological Society of America.

Digby D. Macdonald

University of Auckland, New Zealand: B.Sc., Chemistry (1964)
University of Auckland, New Zealand: M.Sc., Chemistry (1966)
University of Calgary, Canada: Ph.D., Chemistry (1969)

As Director of the Chemistry Laboratory, Physical Sciences Division, SRI, Dr. Macdonald specializes in electrochemistry, corrosion science, and mathematical modeling of physical systems. His research on the corrosion of metals has involved fundamental studies on metal dissolution, stress corrosion cracking, corrosion fatigue, localized corrosion, activity transport in nuclear reactors, and thermodynamic and electrochemical phenomena in aqueous systems.

Dr. Macdonald has also served as Director and Professor at the Fontana Corrosion Center, Ohio State University, and Honorary Associate Professor of Chemistry at the University of Calgary. He was also Senior Research Associate for Alberta Sulfur Research, Ltd., and Assistant Research Officer for Atomic Energy of Canada, Ltd.

Dr. Macdonald has published more than 150 papers in scientific journals, books, and conference proceedings. He is also author of a book on transient techniques in electrochemistry, approximately 50 technical reports, and three patents and numerous patent disclosures. He has delivered more than 100 presentations on his research topics. He belongs to three professional societies and has served on two National Academy of Sciences committees.

Robert A. Paddock

Washington and Lee University: B.S., Physics (1964)
Michigan State University: M.S., Physics (1966)
Michigan State University: Ph.D., Physics (1969)

Dr. Paddock is a geophysicist in the Hydrologic and Geologic Engineering Section of the Geoscience and Engineering Group of the Energy and Environmental Systems Division at Argonne National Laboratory. For more than 12 years, he has served as project leader or team member investigating physical transport of substances in the hydrosphere by way of natural processes and man-made conveyances in the context of energy resources, wastes, and technology development. Dr. Paddock's primary activities have included definition of data requirements, acquisition techniques, and processing schemes; model applications; and data interpretation for model evaluation.

Before joining Argonne as a full-time staff member in 1975, Dr. Paddock was Assistant Professor of Physics at Ripon College. While on the faculty, Dr. Paddock spent several semesters as a Resident Research Associate at Argonne working in the area of physical transport in the hydrosphere.

Dr. Paddock has authored more than 30 scientific and technical publications and has served as a reviewer of technical papers for the Hydraulics Division of the American Society of Civil Engineers.

James P. Peerenboom

University of Wisconsin-Madison, B.S., Nuclear Engineering (1973)
University of Wisconsin-Madison, M.S., Nuclear Engineering (1974)
University of Wisconsin-Madison, Ph.D., Energy and Environmental Systems, Land Resources Program (1981)

As an Energy Systems Engineer with the Energy and Environmental Systems Division of Argonne National Laboratory, Dr. Peerenboom has participated in numerous projects involving electric utility systems, technology evaluation, risk comparison, and decision analysis. He is currently developing a decision methodology for determining research priorities for the DOE magnetic fusion program, a microcomputer-based environmental impact model for energy planning in developing countries, and analytical models for examining electric utility emissions. In addition, Dr. Peerenboom led the effort to develop a formalized budget allocation procedure (based on decision analysis) to help the chairman of the DOE Steering Committee on Supplemental Environmental Programs for the Great Plains Coal Gasification Project establish research priorities and determine detailed budget allocation recommendations.

Before joining Argonne, Dr. Peerenboom worked as a Research Assistant in the Energy Systems and Policy Research Program at the University of Wisconsin-Madison (1977-1981), where he developed a decision-analysis approach to energy system expansion planning. From 1980 to 1981, Dr. Peerenboom worked as a Consultant for Resource Management Associates; in 1980, he was a Fellow for the East-West Environmental and Policy Institute; and in 1977, he was a Visiting Scientist at Brookhaven National Laboratory and at the International Institute for Applied Systems Analysis in Austria. From 1974-1976, Dr. Peerenboom was a Research Associate at Oak Ridge National Laboratory.

Dr. Peerenboom has published more than 25 technical reports, journal articles, and conference papers, and has contributed to guidebooks for the International Atomic Energy Agency. He is a member of the American Nuclear Society, the Society for Risk Analysis, and Tau Beta Pi.

Gary S. Was

University of Michigan: B.S., Nuclear Engineering (1975)
Massachusetts Institute of Technology: S.M., Nuclear Engineering (1977)
Massachusetts Institute of Technology: Sc.D., Nuclear Materials Engineering (1980)

After a year of postdoctoral research at the Massachusetts Institute of Technology, Dr. Was became Assistant Professor in the Department of Nuclear Engineering at the University of Michigan. He was promoted to Associate Professor in 1985. From 1978 to 1980, he was Staff Scientist for Entropy, Ltd., where he helped develop a fuel performance and reliability computer code system. He also spent a summer (1974) working for the U.S. Environmental Protection Agency on developing a model for radiation transport through effluent pathways.

Dr. Was researches the effects of impurities on the susceptibility of austenitic alloys to intergranular cracking at both high and low temperatures in aqueous environments and the effect of ion irradiation on the physical and mechanical properties of alloy surfaces. His achievements have included significant advances in understanding chromium depletion in nickel-base alloys, characterizing quantitatively the electrochemical behavior of chromium-depleted zones in austenitic alloys, and developing models to describe the performance of stainless steel fuel cladding in light-water nuclear reactors. He has also advanced the understanding of the thermodynamics and kinetics of metastable phase formation under ion irradiation.

Dr. Was is author and coauthor of more than 21 publications and has presented his research at 20 conferences. He is a member of six professional and honorary societies and was selected a Presidential Young Investigator in 1985.